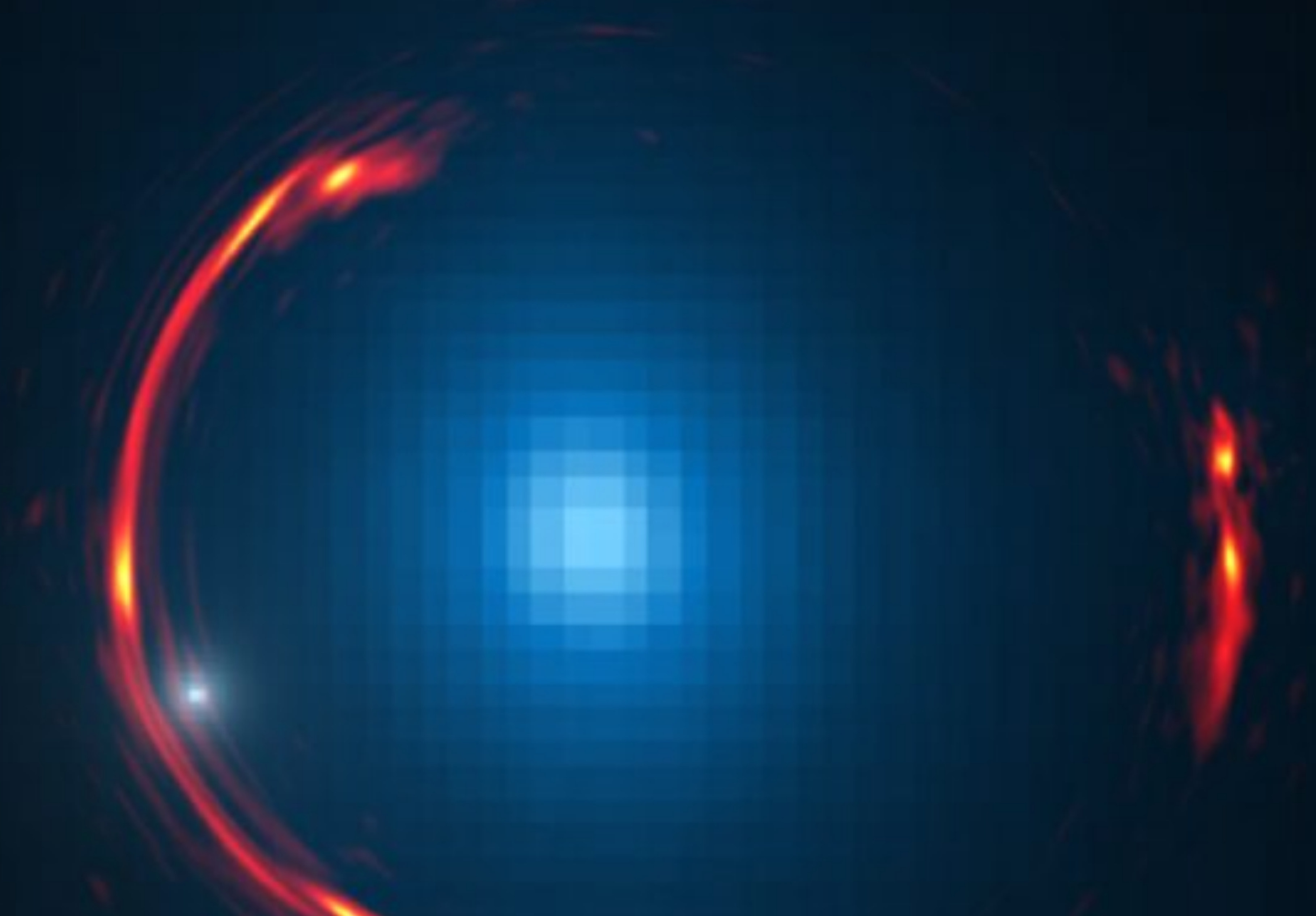
HUNTING FOR DARK MATTER SUBSTRUCTURES IN STRONG LENSING WITH NEURAL NETWORKS



JOSHUA YAO-YU LIN (UIUC PHYSICS)

MACHINE LEARNING FOR PHYSICS AND THE PHYSICS OF LEARNING WORKSHOP, IPAM UCLA I 2019.9.26

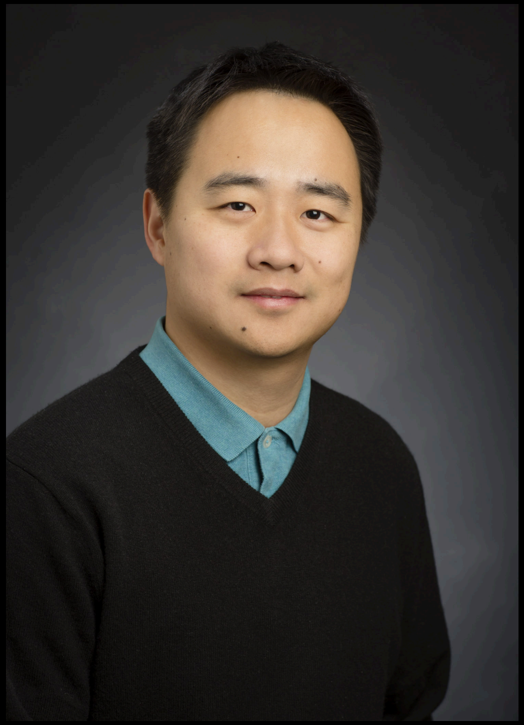
Lin et al. 2019 (In prep)

PEOPLE I WORK WITH

LOCAL GROUP

Hang Yu
[UIUC]

Warren
Morningstar
[Stanford]



Jian Peng
[CS@UIUC]

Gil Holder
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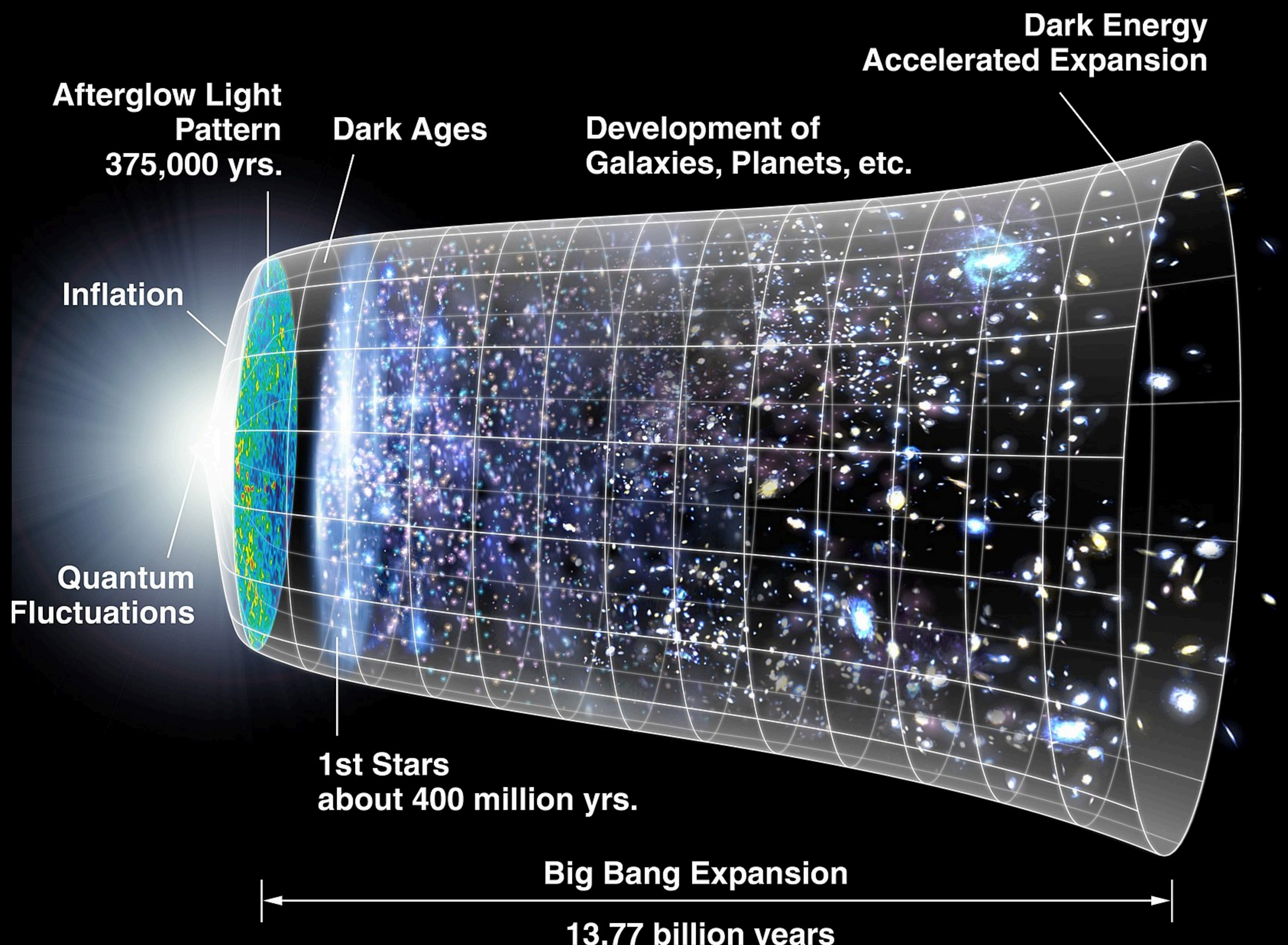
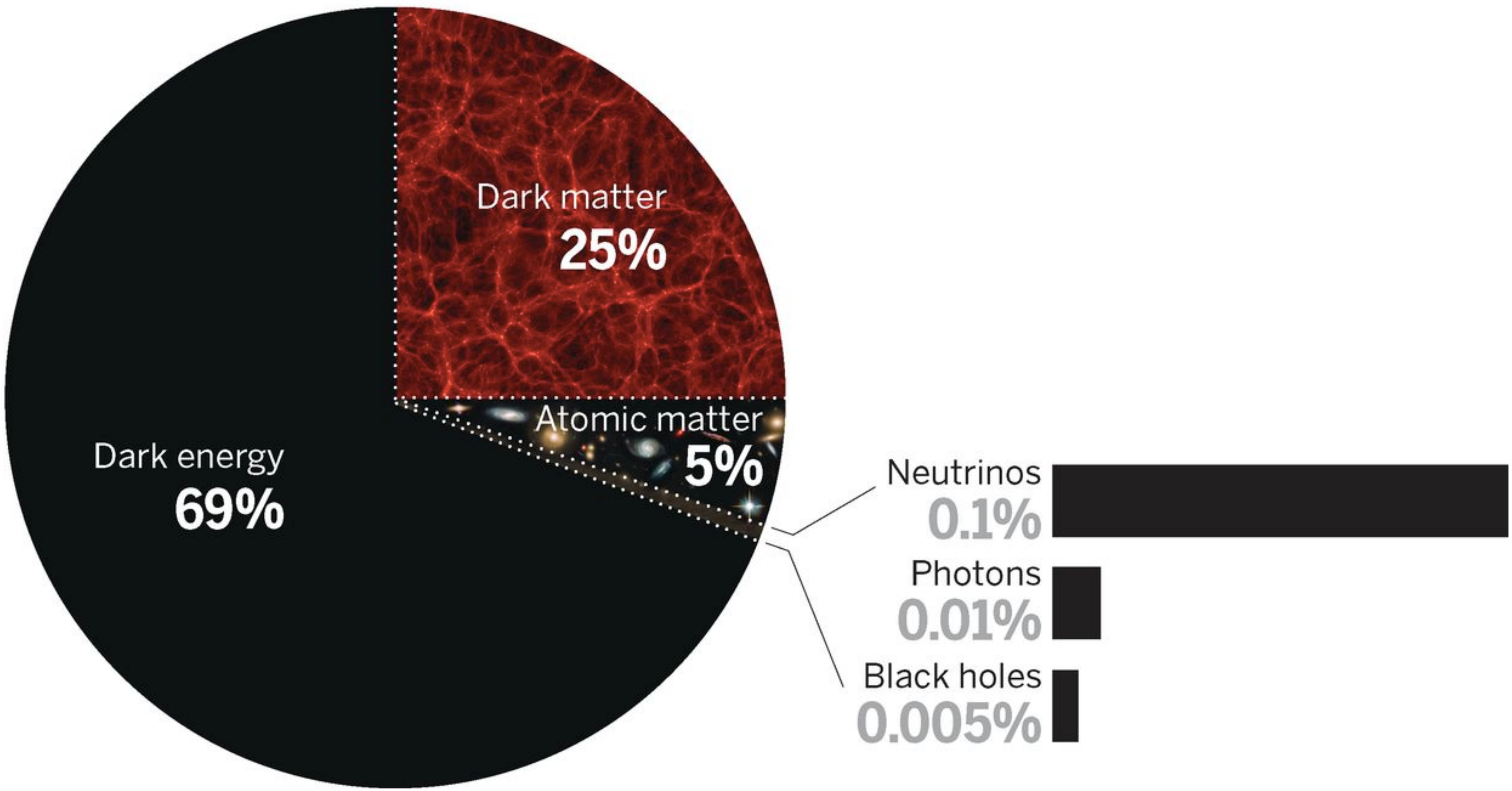


Image Credit: NASA/WMAP

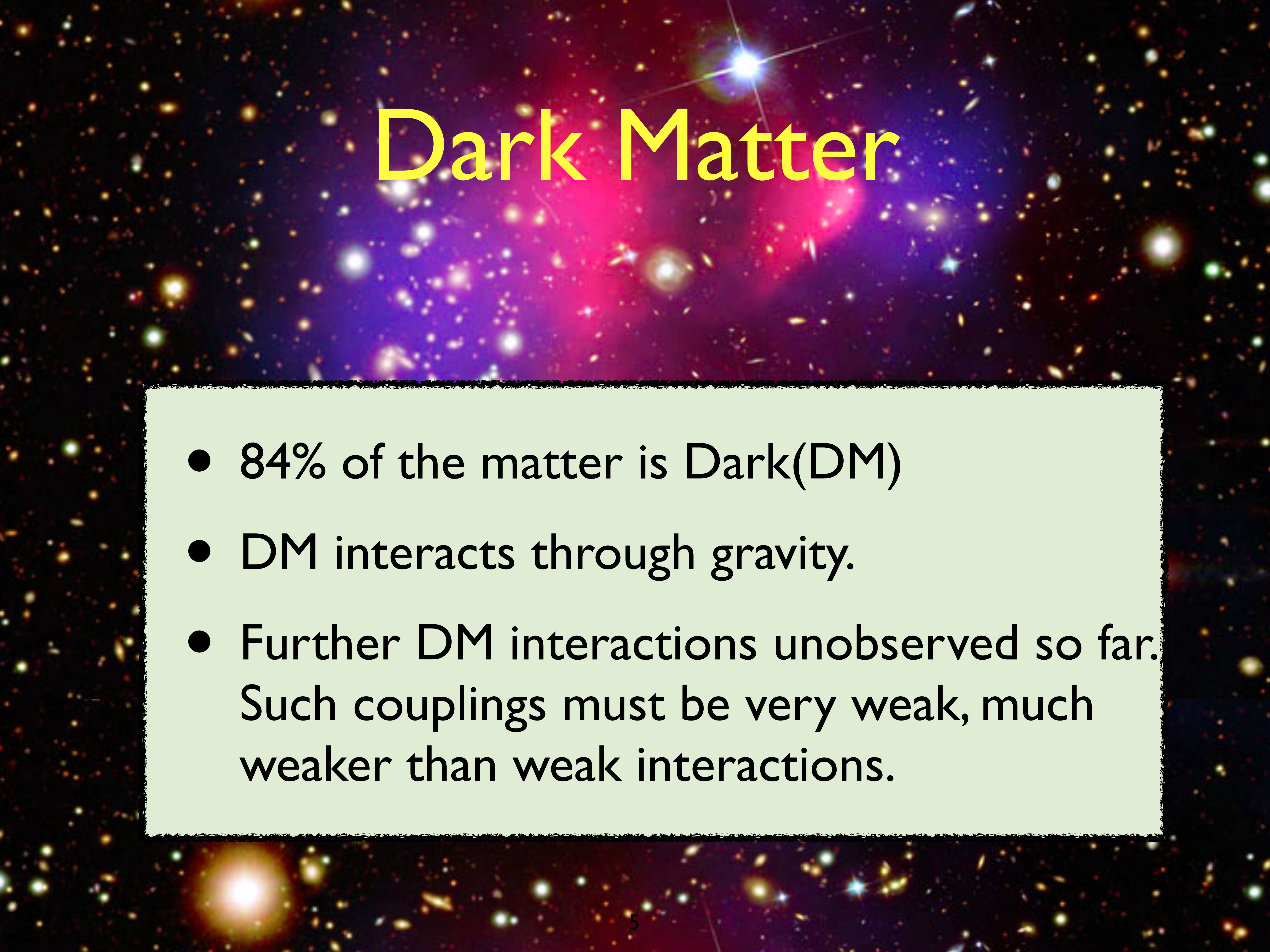
The multiple components that compose our universe

Current composition (as the fractions evolve with time)



Three different types of neutrinos comprise at least 0.1%, the cosmic background radiation makes up 0.01%, and black holes comprise at least 0.005%.

David Spergel (Science, 2015)

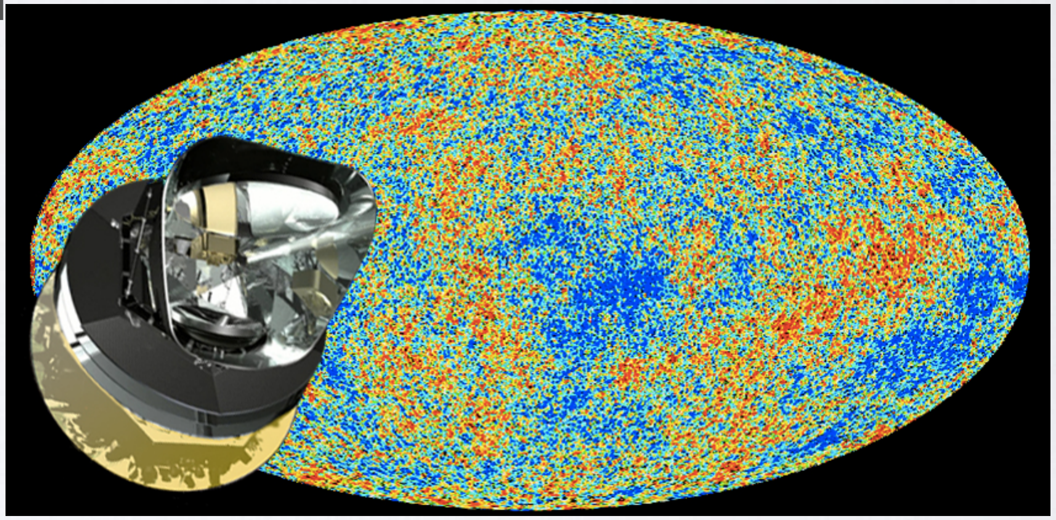


Dark Matter

- 84% of the matter is Dark(DM)
- DM interacts through gravity.
- Further DM interactions unobserved so far. Such couplings must be very weak, much weaker than weak interactions.

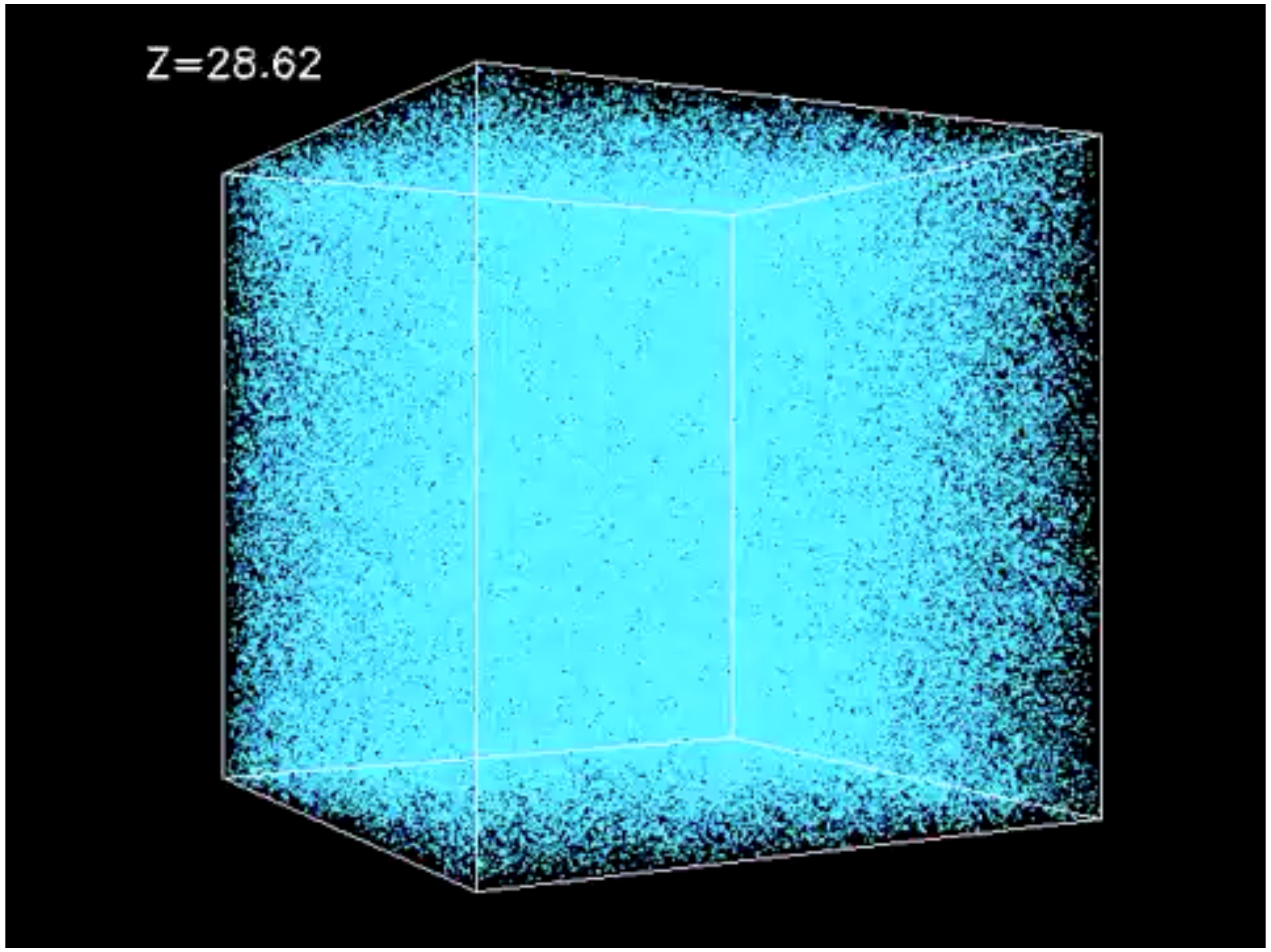
PROPERTY OF DM?

- Early time evolution (linear regime): **Cosmological Perturbation Theory** [See Modern Cosmology by S. Dodelson, or CP Ma, E Bertschinger arXiv: 9506072]: **cosmic microwave background**



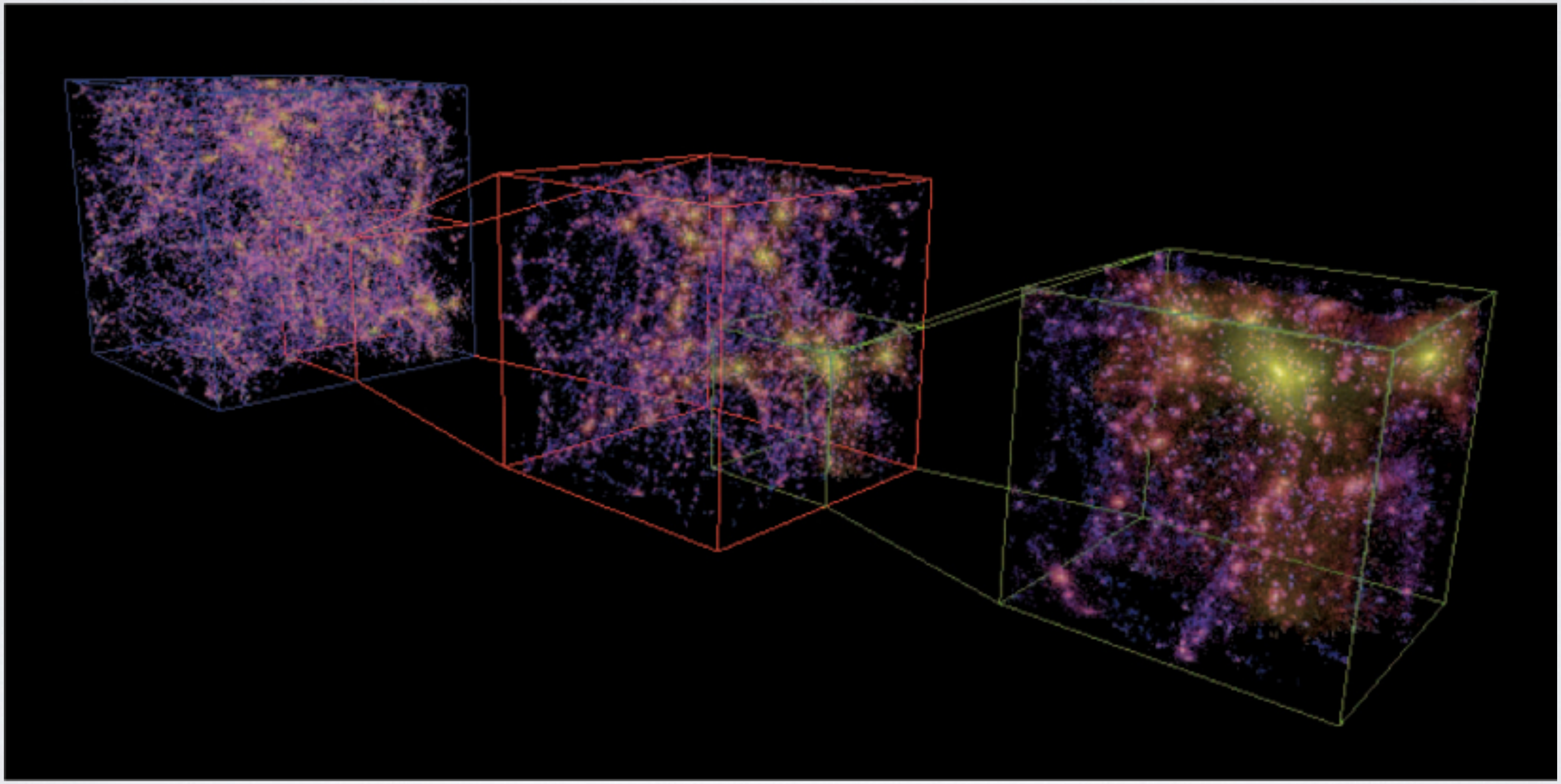
- Late time evolution (Non-linear): **N-Body Simulation**: **Large-scale structure**

N-Body Simulation of Cold Dark Matter



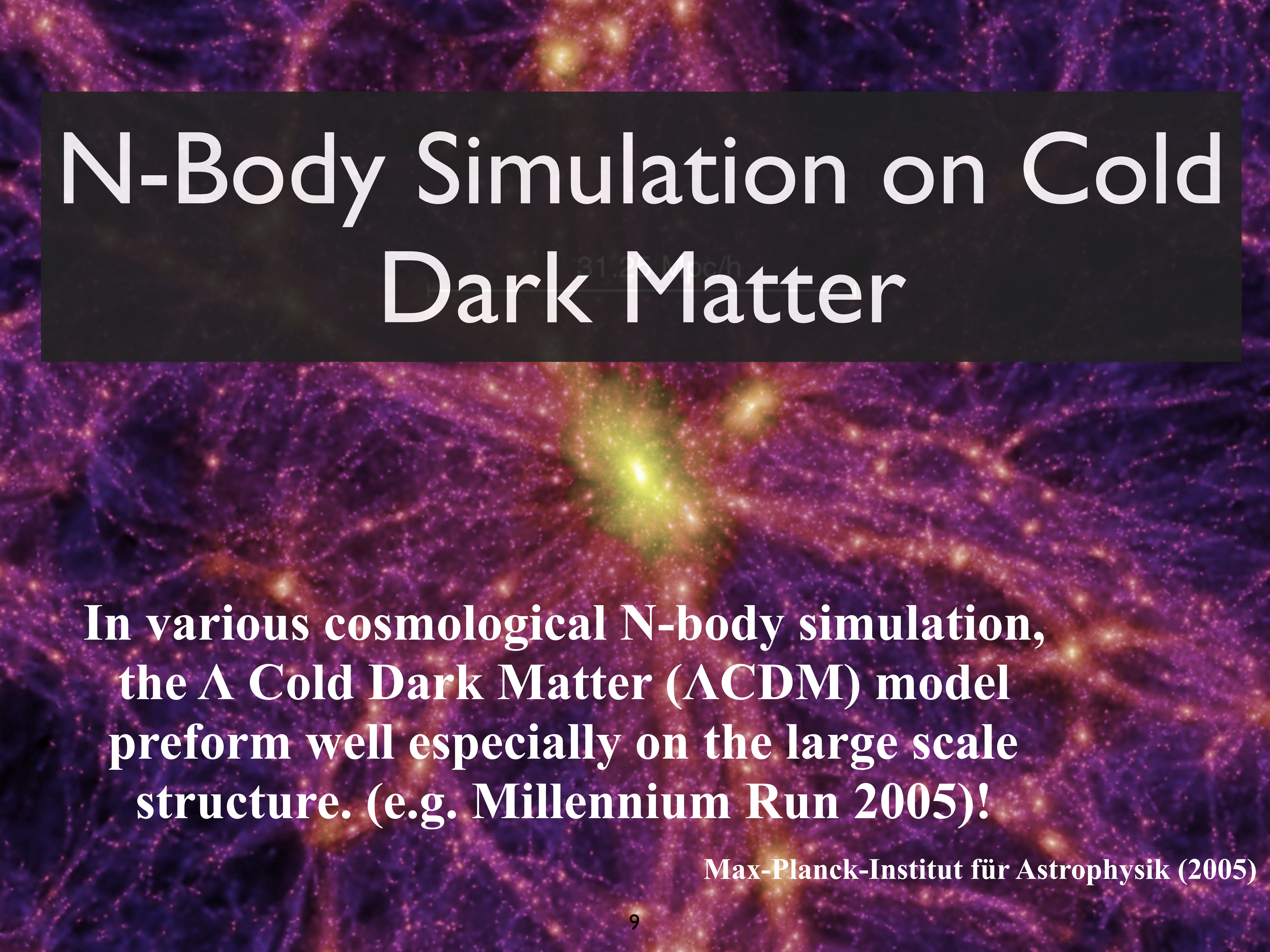
Simulation by Andrey Kravtsov (The University of Chicago) and Anatoly Klypin (New Mexico State University)

N-BODY SIMULATION: DARK MATTER



Max-Planck-Institut für Astrophysik (2005)

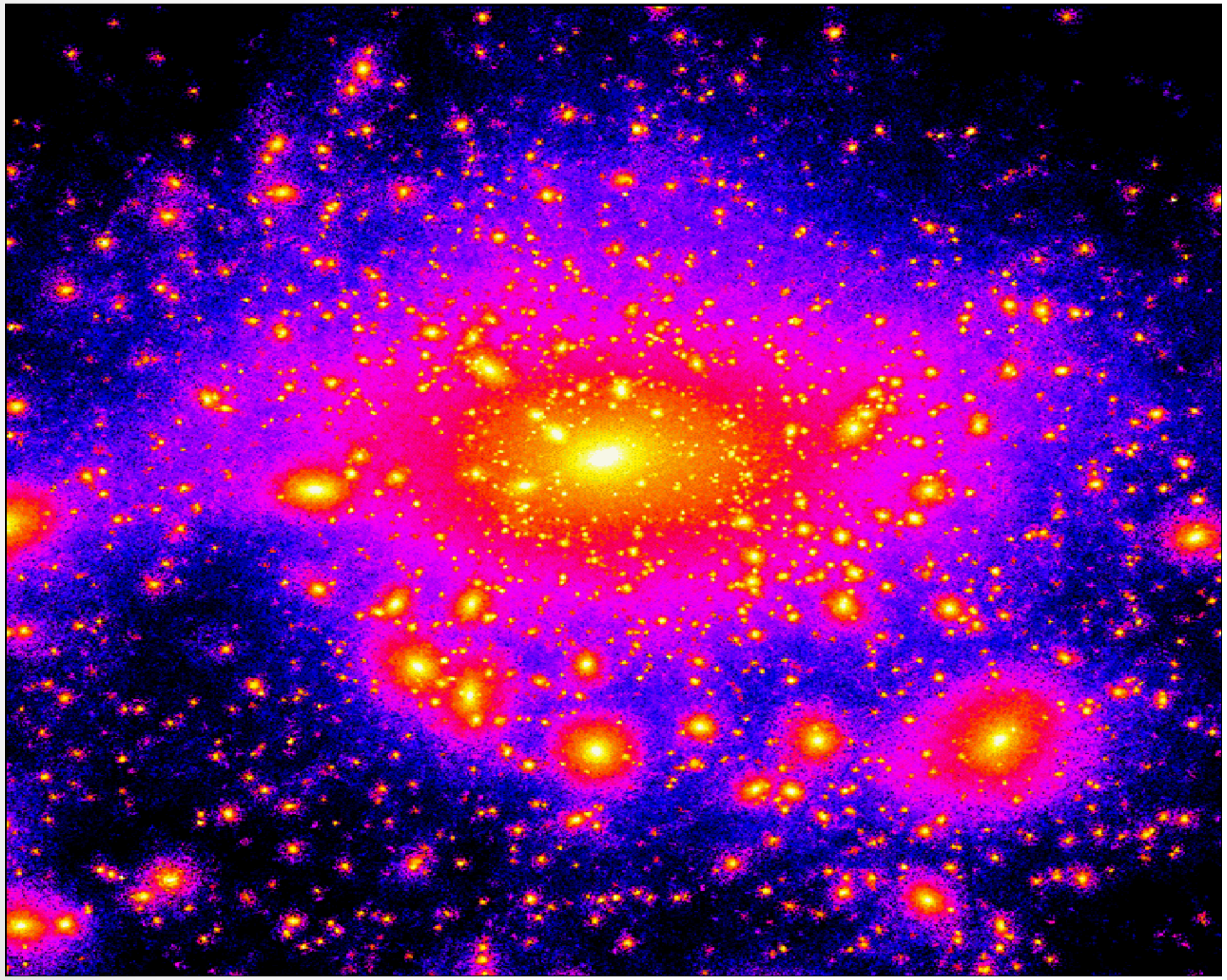
N-Body Simulation on Cold Dark Matter



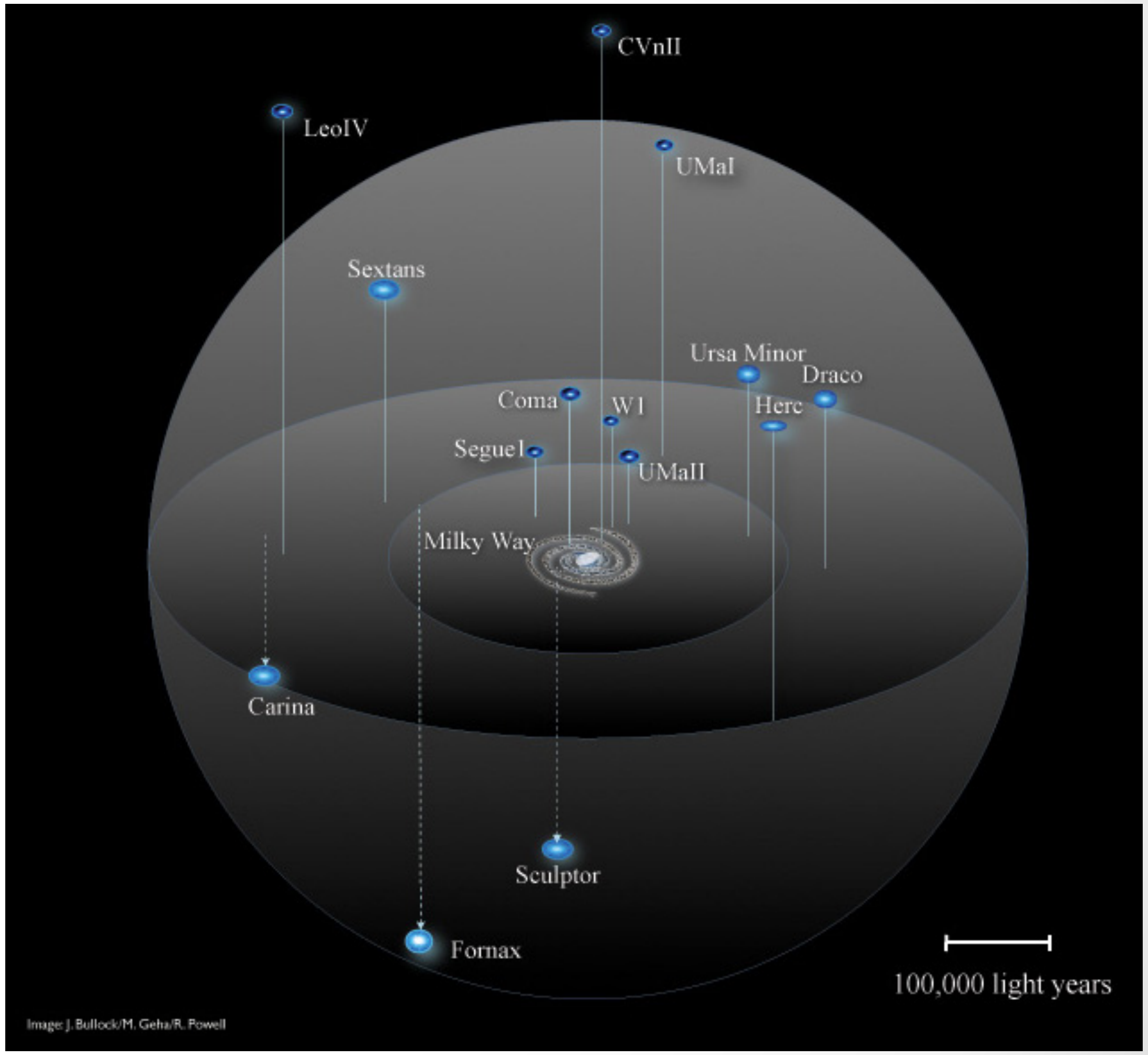
In various cosmological N-body simulation, the Λ Cold Dark Matter (ΛCDM) model preform well especially on the large scale structure. (e.g. Millennium Run 2005)!

Max-Planck-Institut für Astrophysik (2005)

Missing Satellites Problem



CDM Simulation (Mayer and Kazantzidis)



Satellite galaxies of the Milky Way (Observation)

Credit: J. Bullock, M. Geha, R. Powell

Strong lensing: Natural place to probe dark matter substructures

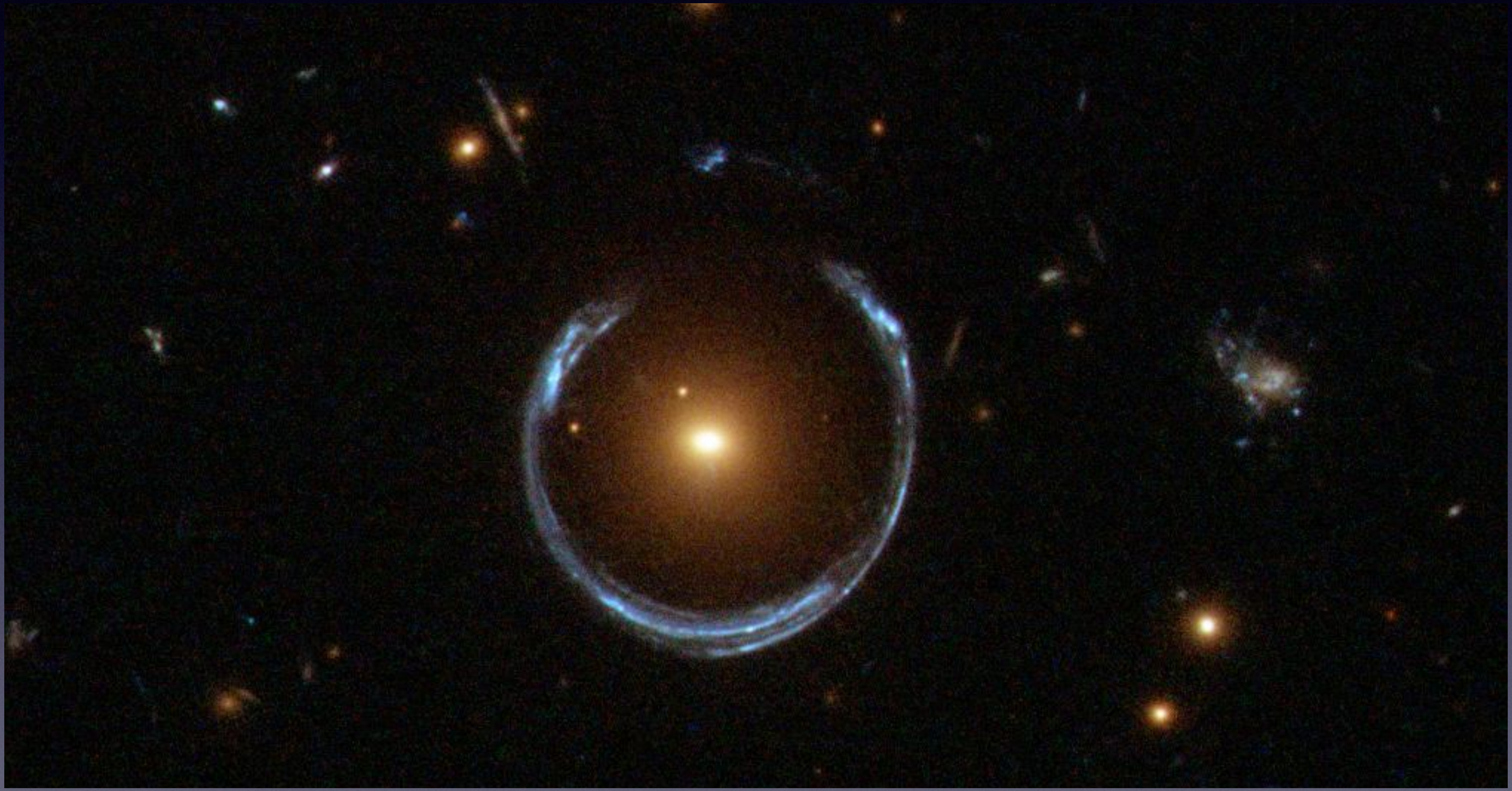
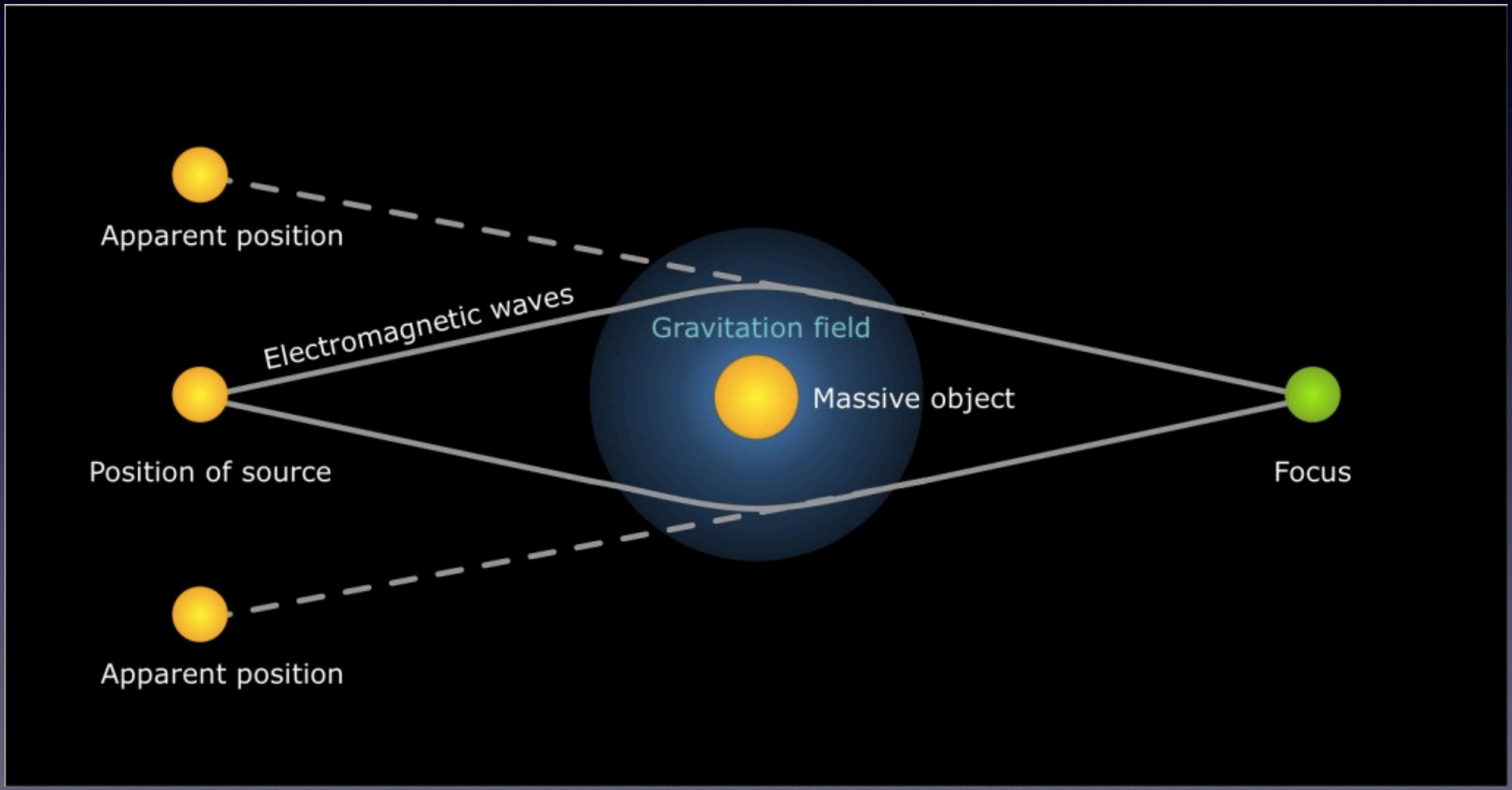


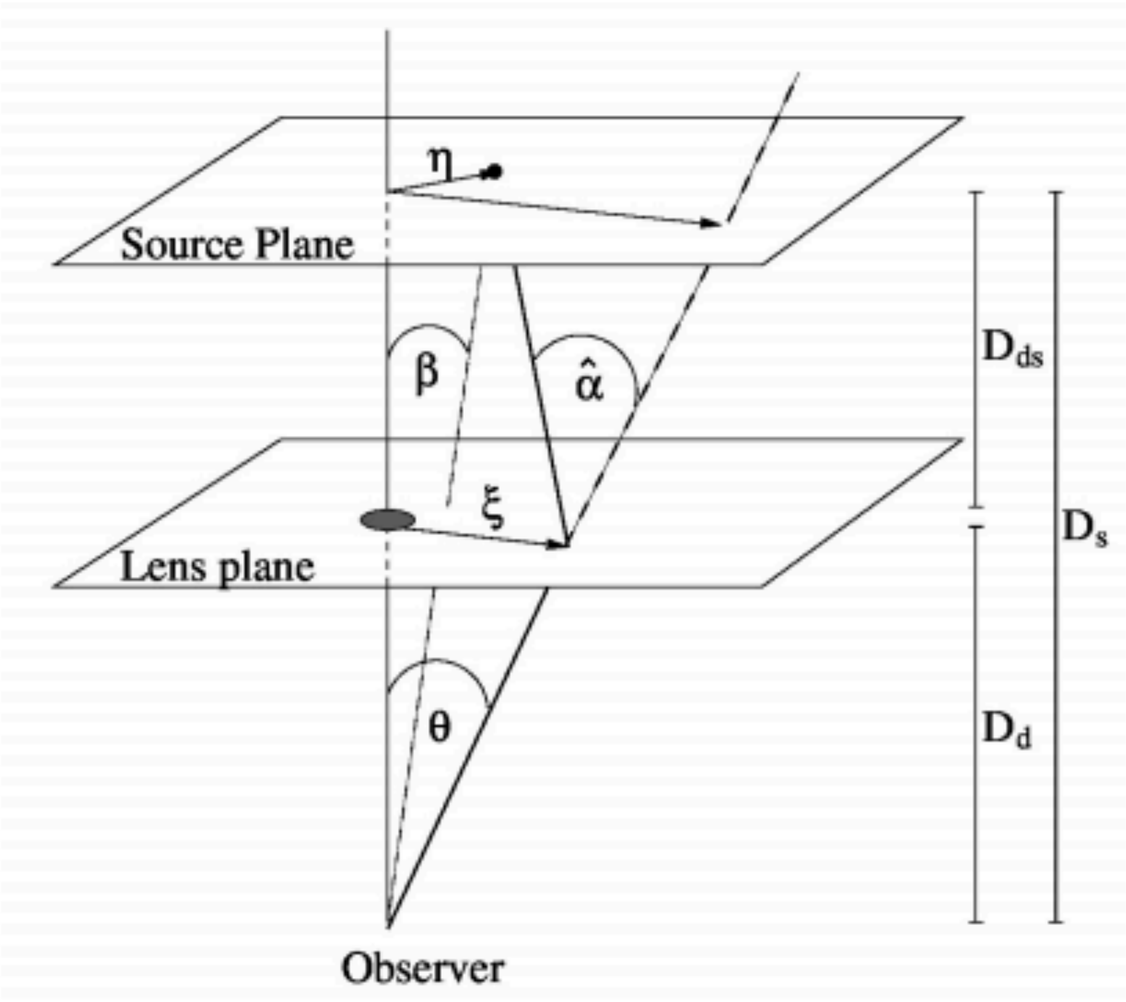
Image credit: ESA/Hubble & NASA

Strong lensing



Lensing basic

Lens equation



[Schneider et al. 2006]

$$\boldsymbol{\eta} = \frac{D_\mathrm{s}}{D_\mathrm{d}}\boldsymbol{\xi} - D_\mathrm{ds}\hat{\boldsymbol{\alpha}}(\boldsymbol{\xi})$$

In terms of angular coord.:

$$\boldsymbol{\eta} = D_\mathrm{s}\boldsymbol{\beta}$$

$$\boldsymbol{\xi} = D_\mathrm{d}\boldsymbol{\theta}$$

$$\boxed{\boldsymbol{\beta} = \boldsymbol{\theta} - \boldsymbol{\alpha}(\boldsymbol{\theta})}$$

where

$$\boldsymbol{\alpha}(\boldsymbol{\theta}) = \frac{D_\mathrm{ds}}{D_\mathrm{s}}\hat{\boldsymbol{\alpha}}(D_\mathrm{d}\boldsymbol{\theta})$$

2

Slides credit: Sherry Suyu

Lensing basic: caustic & critical curve

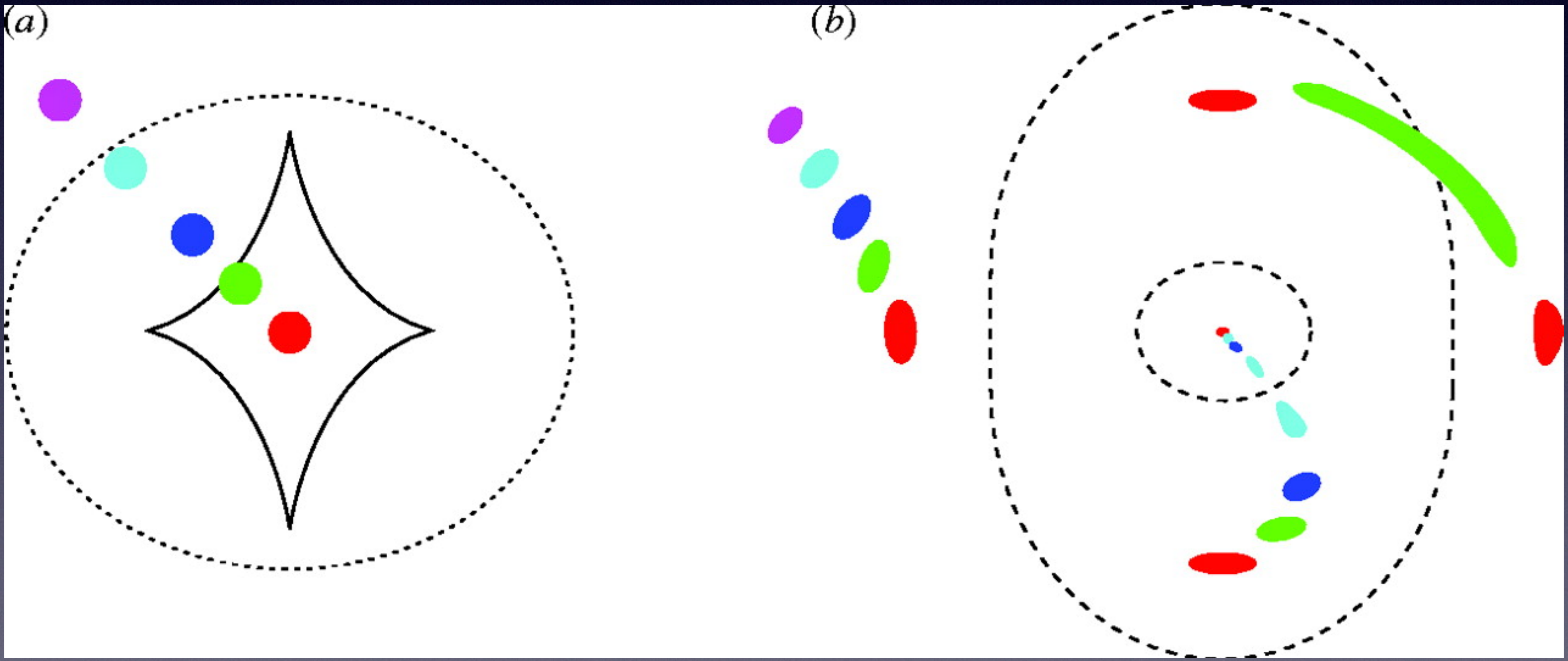
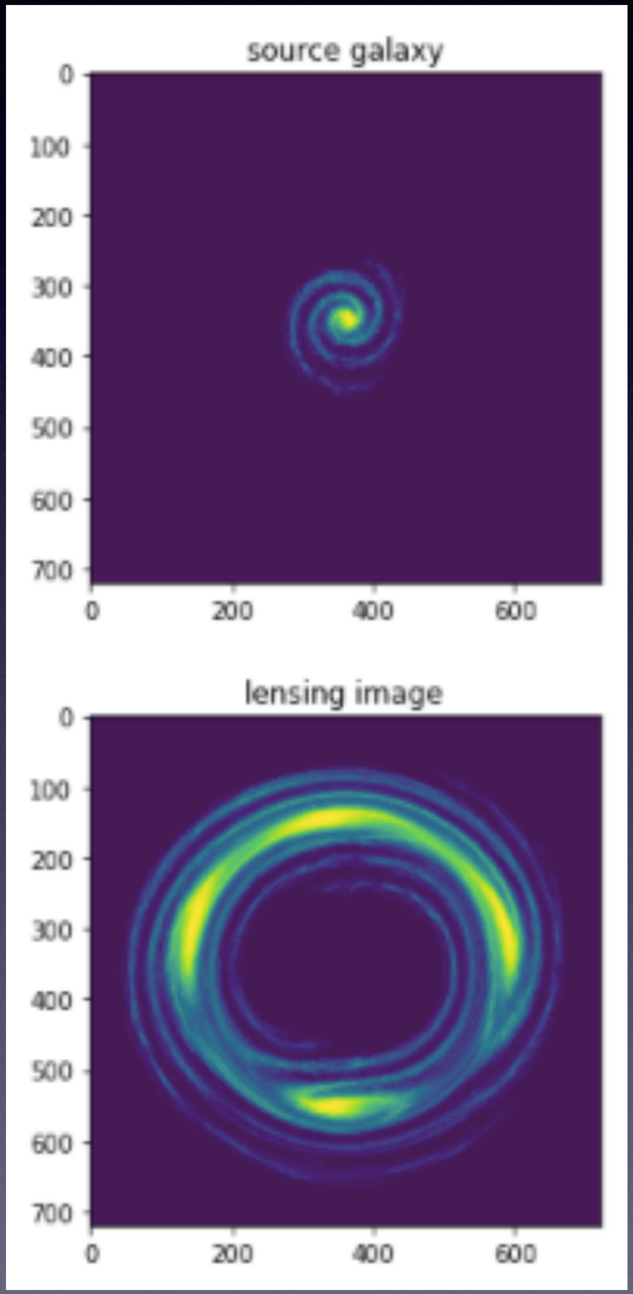
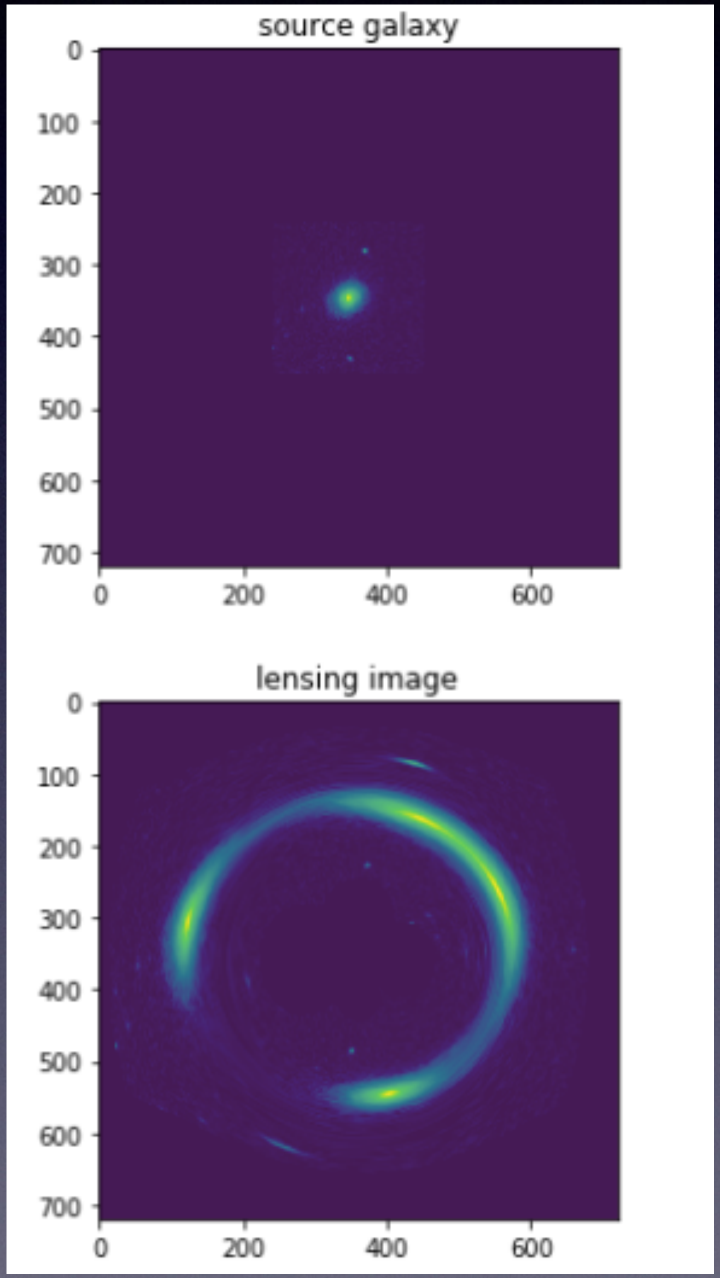


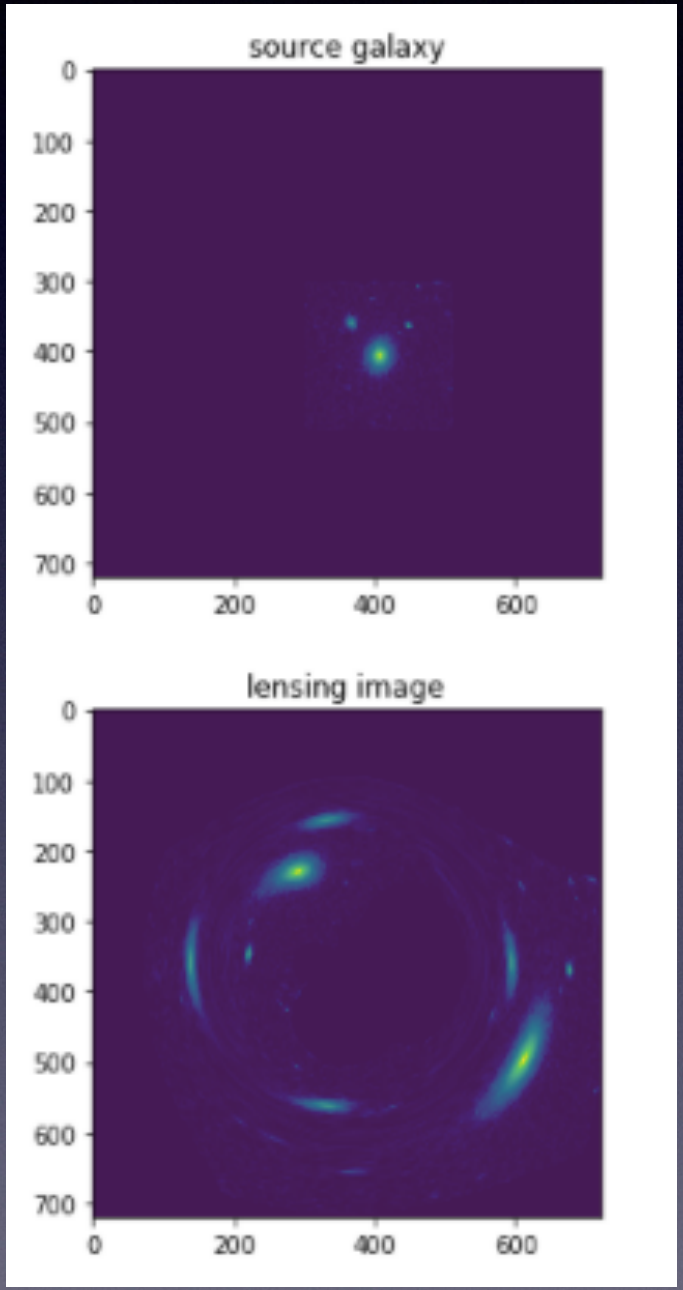
Figure from Narayan & Bartelmann (1995)

Strong lensing simulations





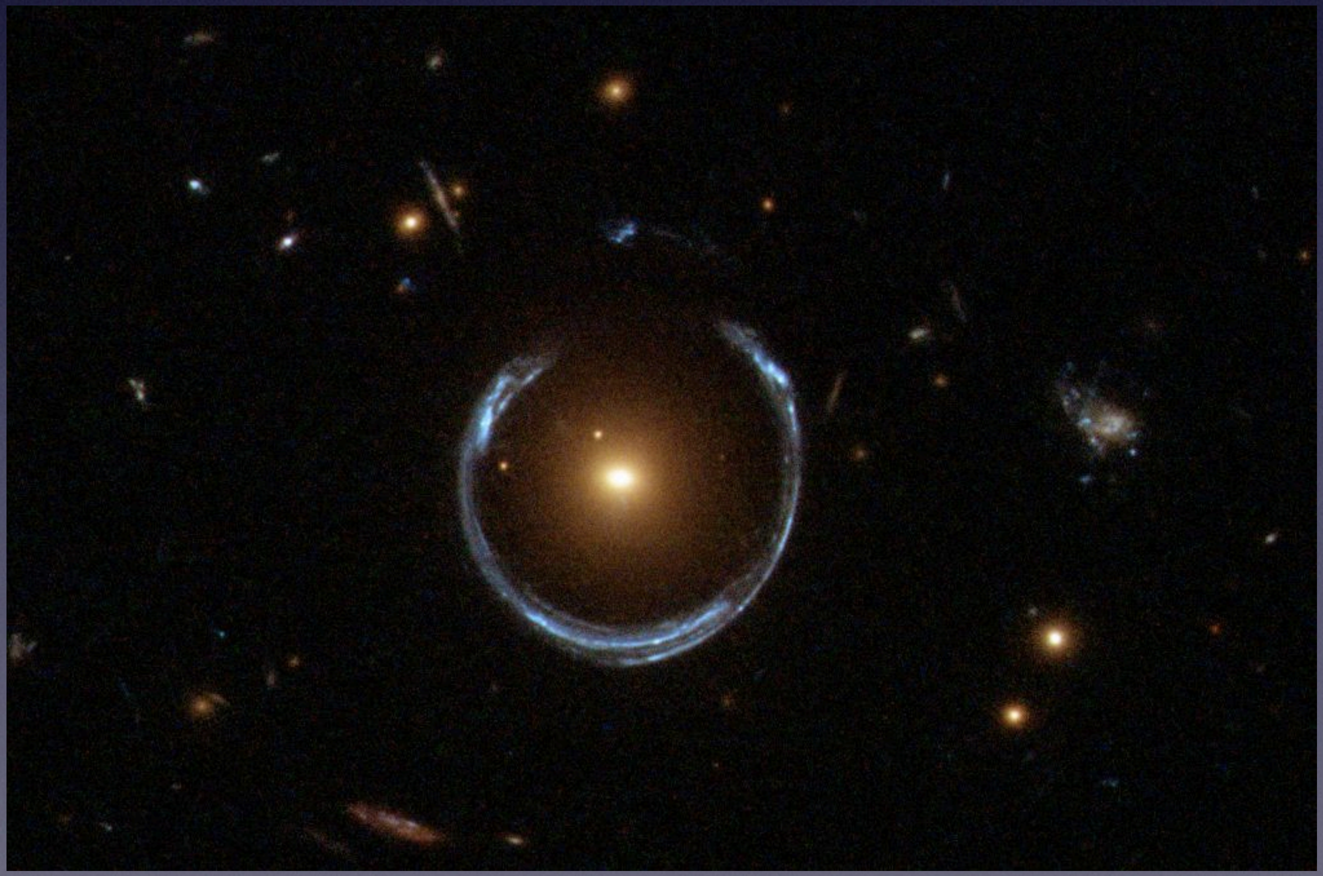
Lensing image



Lensing image

Strong lensing for subhalos: Two approaches

- gravitational imaging vs flux ratio anomalies



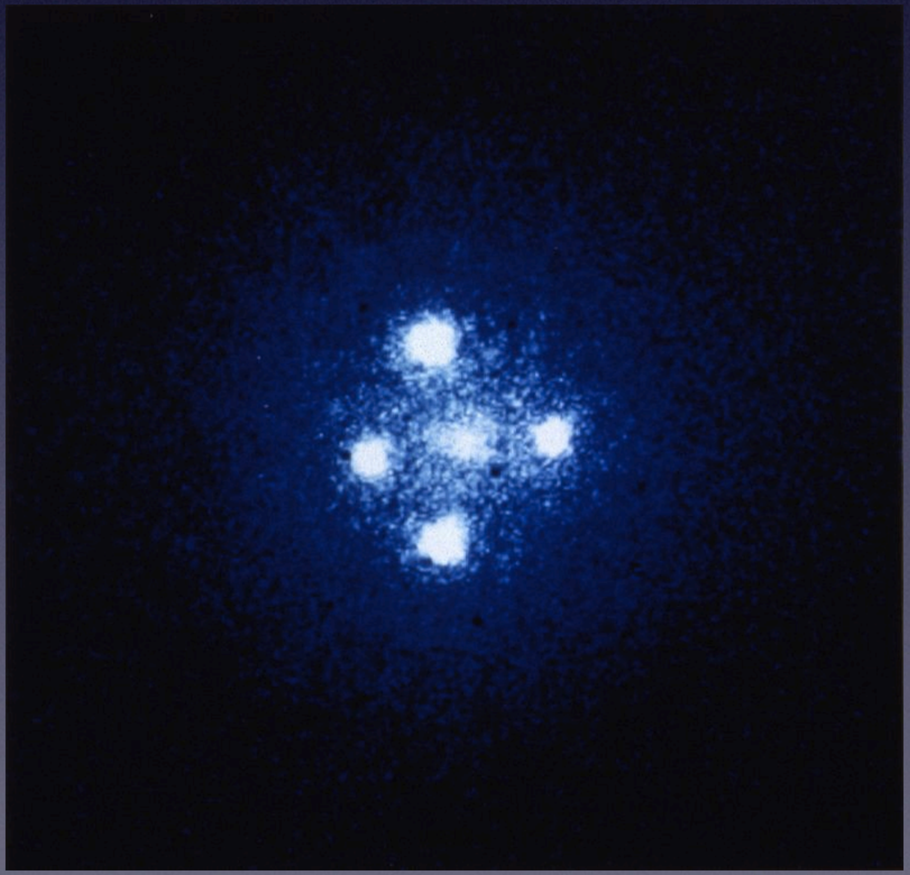


Image credit: NASA, ESA, Hubble, and STScI

Subhalo detection

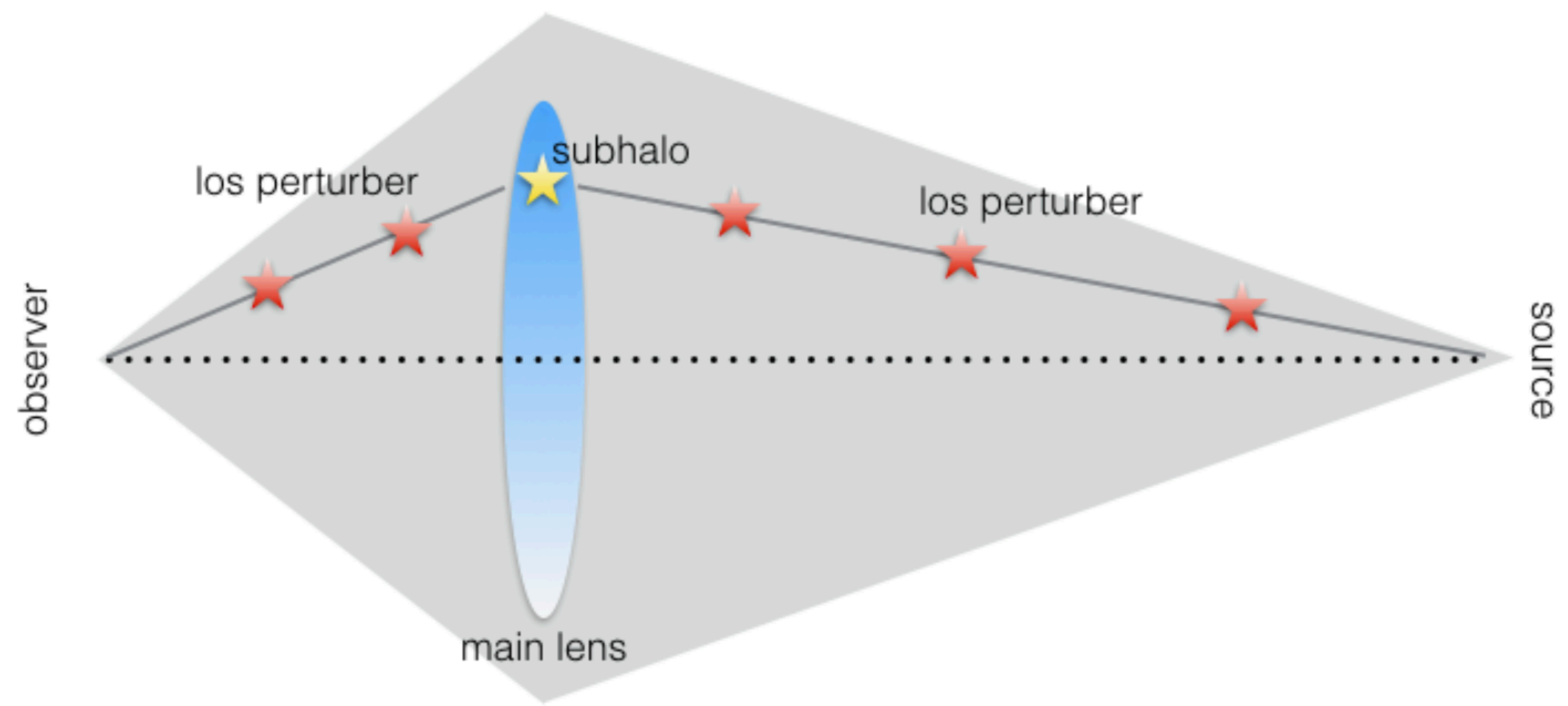
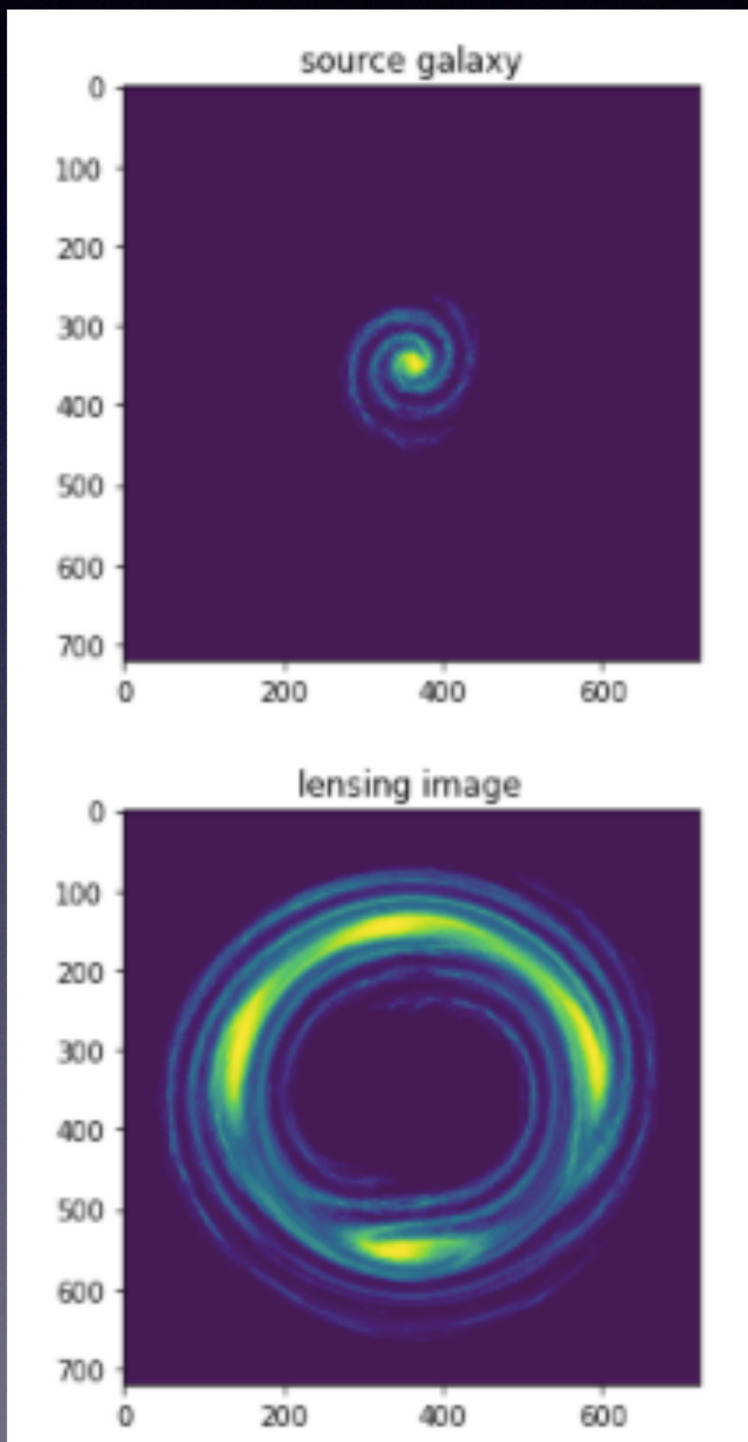


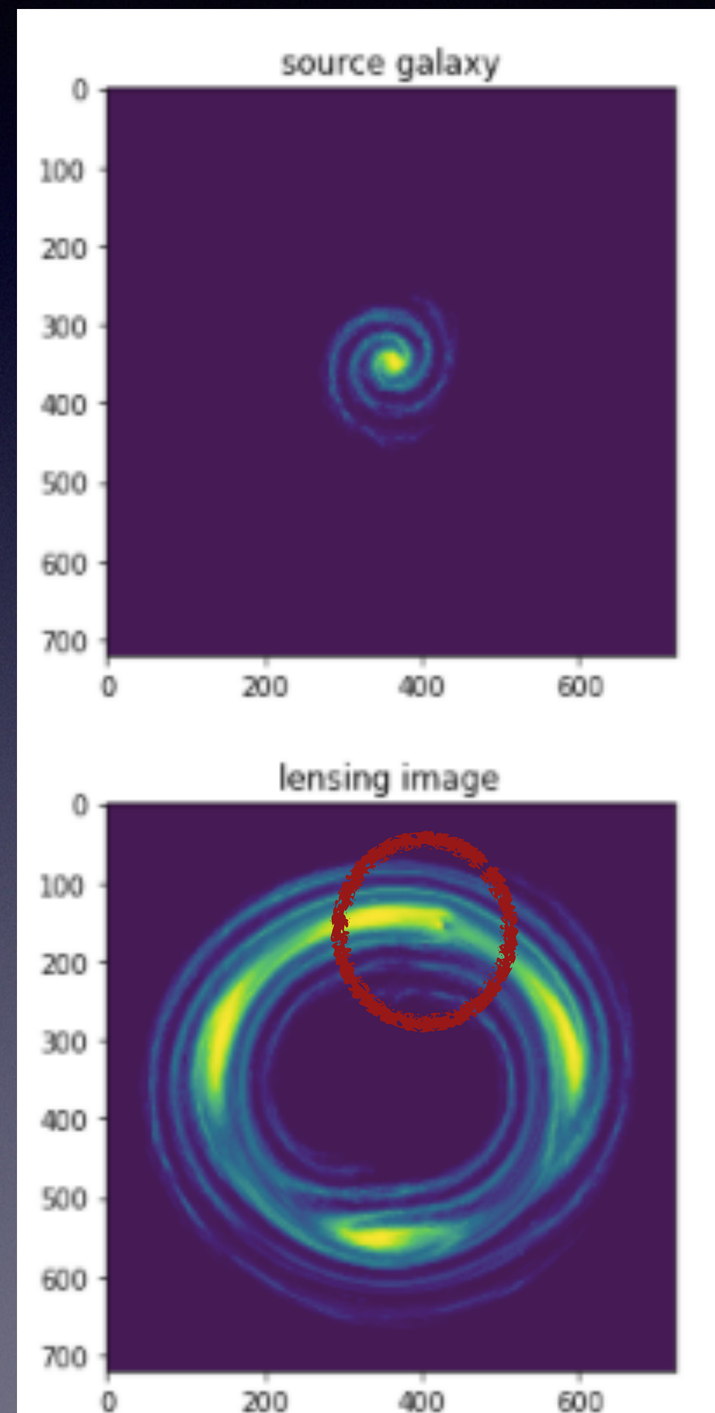
Figure 2. A simple sketch of the method we used to create our mock data; subhaloes and line-of-sight haloes are placed so that their lensing effect lies in the same projected position on the plane of the main lens; the grey region gives an example of the line-of-sight volume that is taken into account.

Despali et al. (1710.05029)

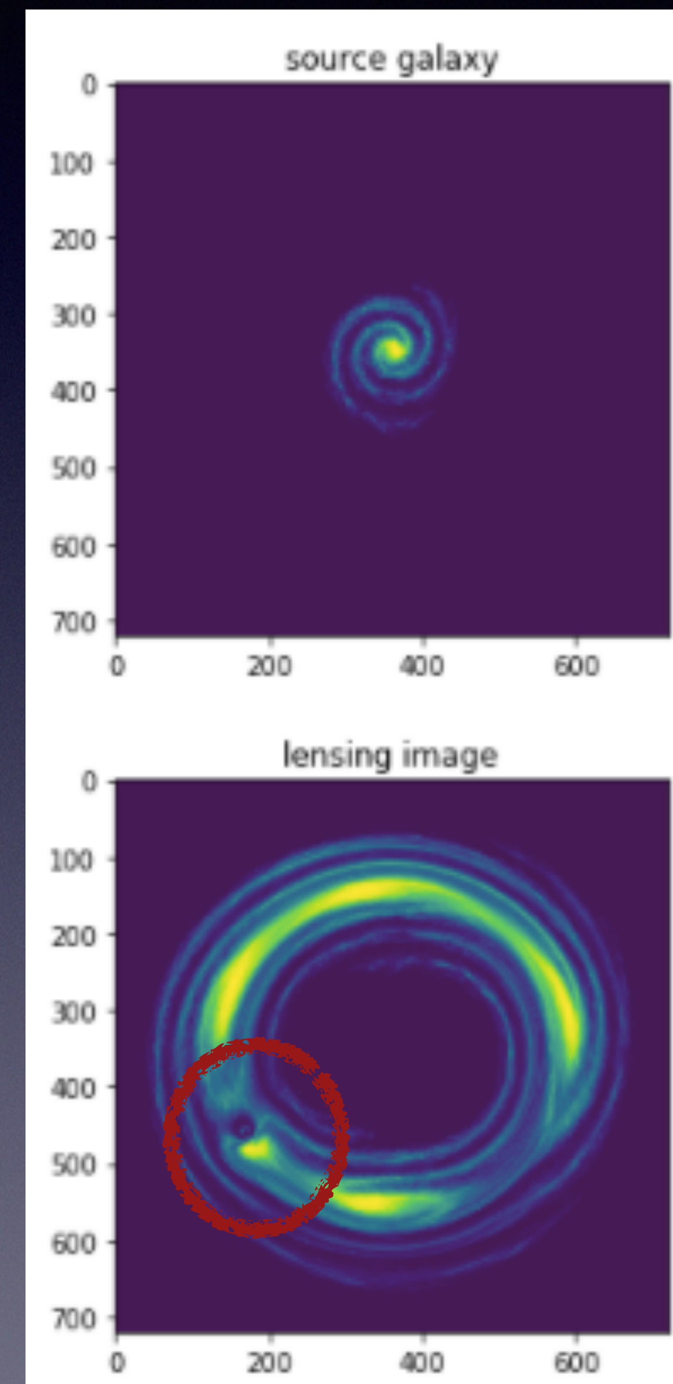
Strong lensing with substructure as perturber



Smooth Lensing

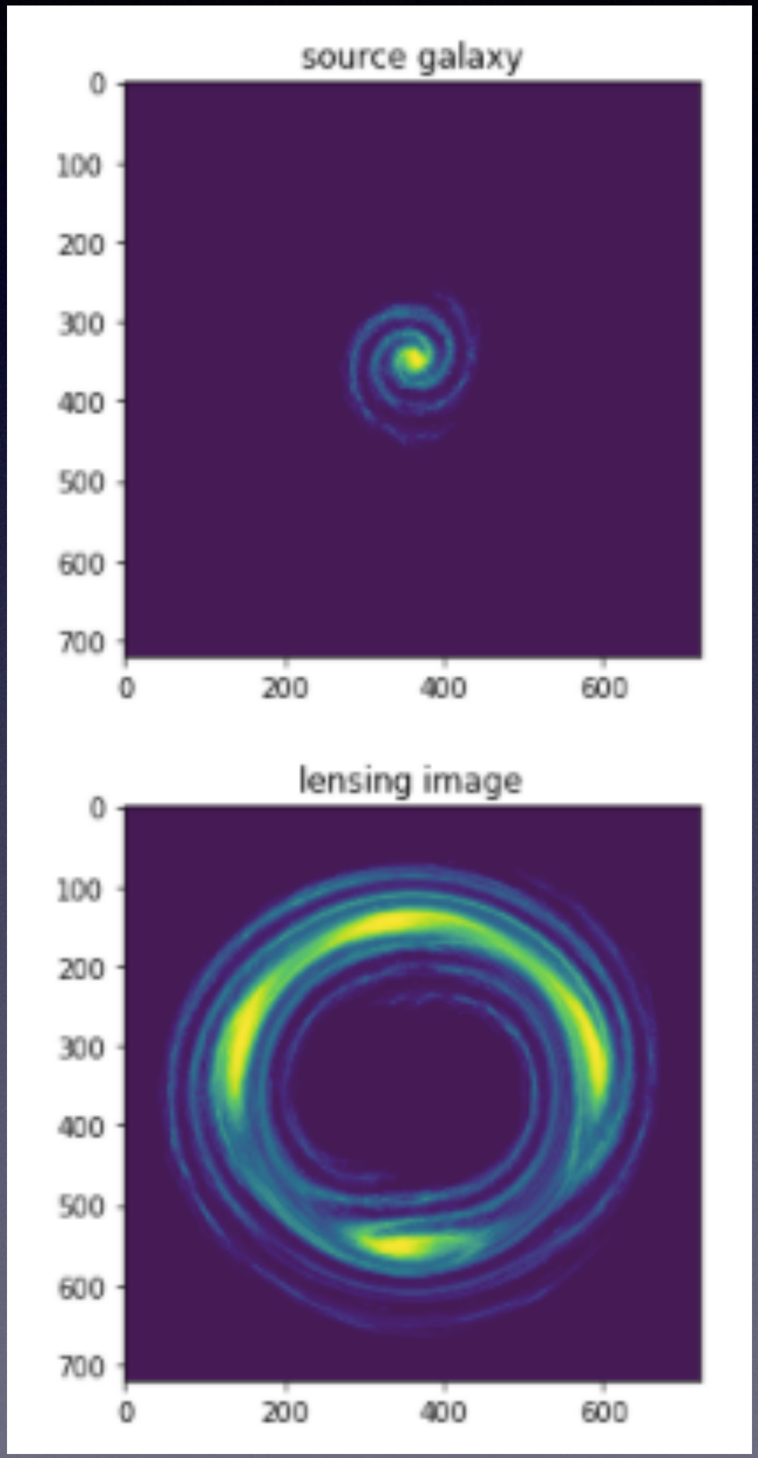


Lensing with perturber



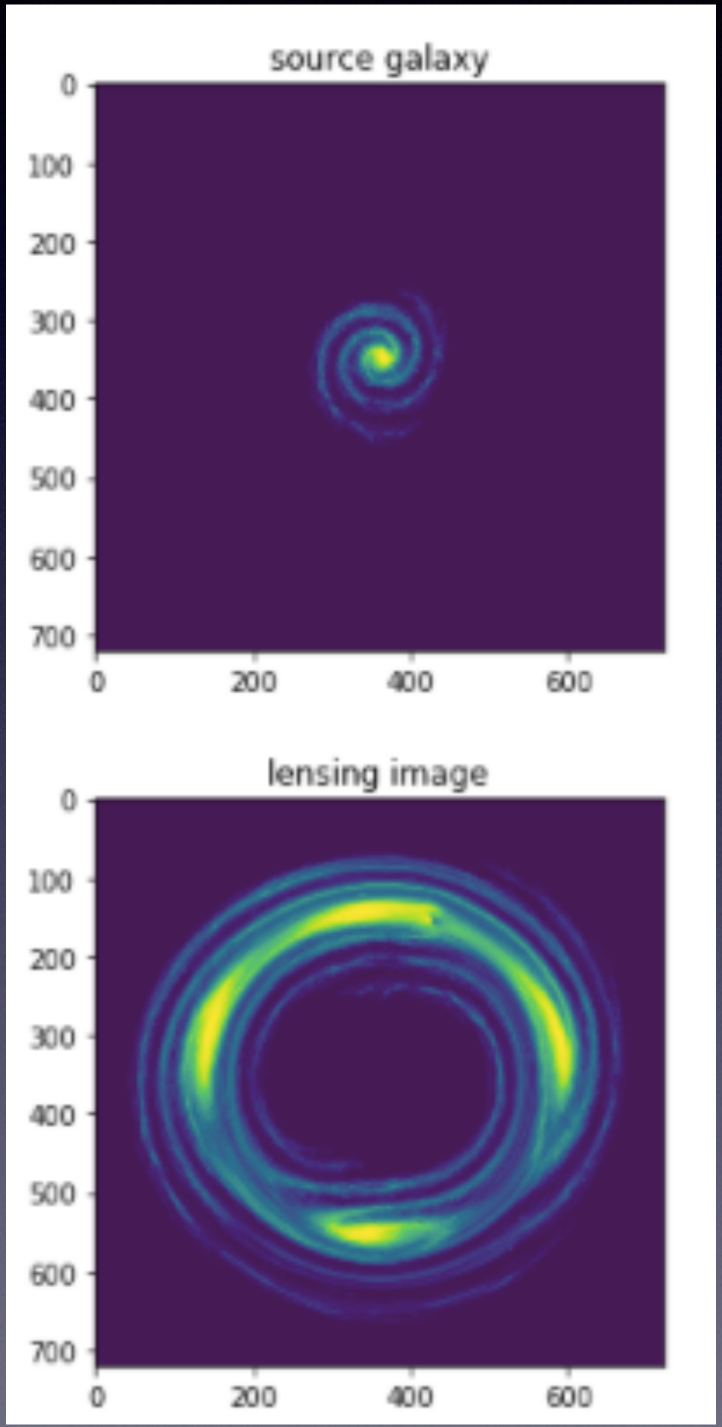
Lensing with (large) massive perturber

Strong lensing with substructure as perturber



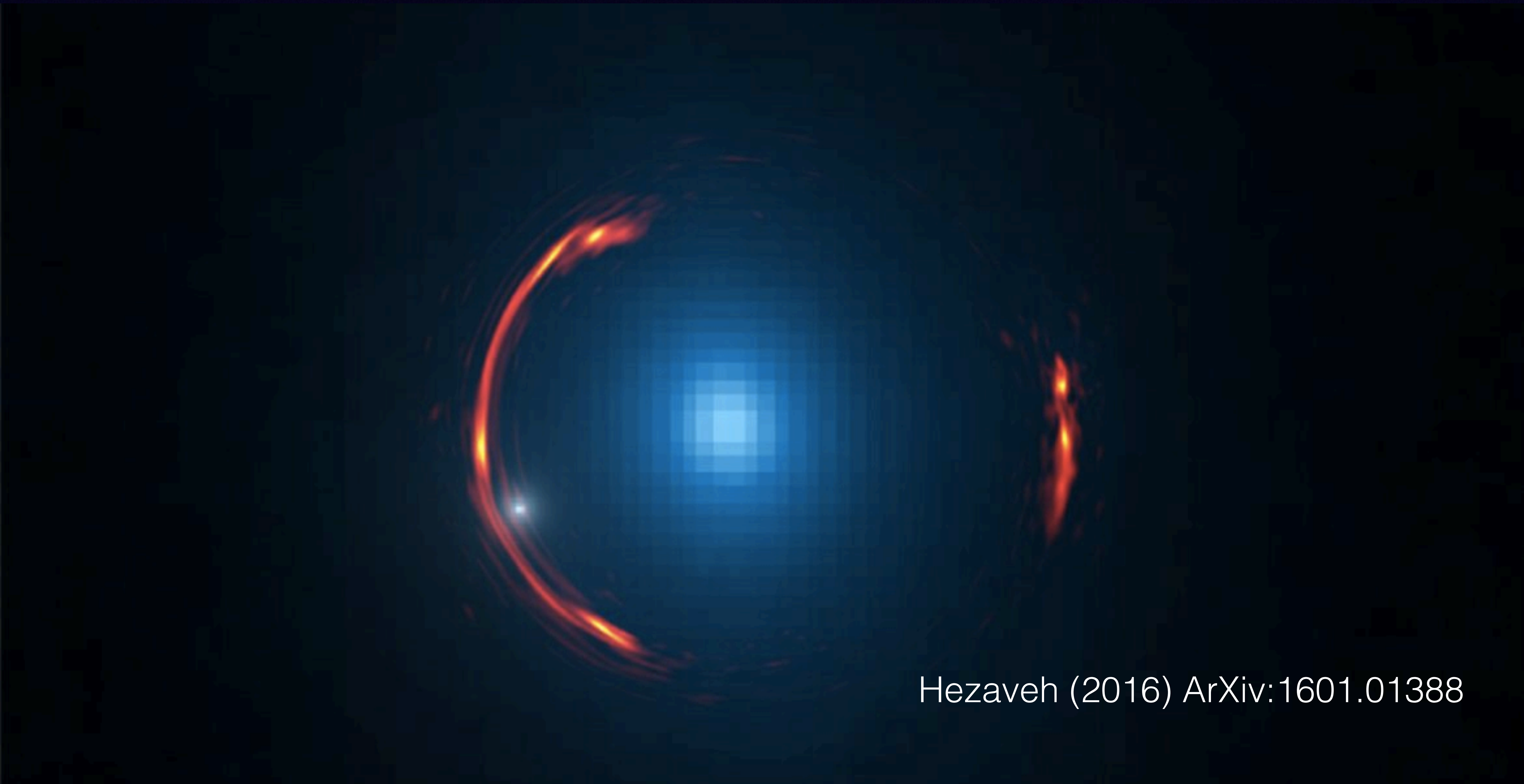
Smooth Lensing

Strong lensing with substructure as perturber



Lensing with perturber

Subhalo Hidden in ALMA Gravitational Lens Image



Hezaveh (2016) ArXiv:1601.01388

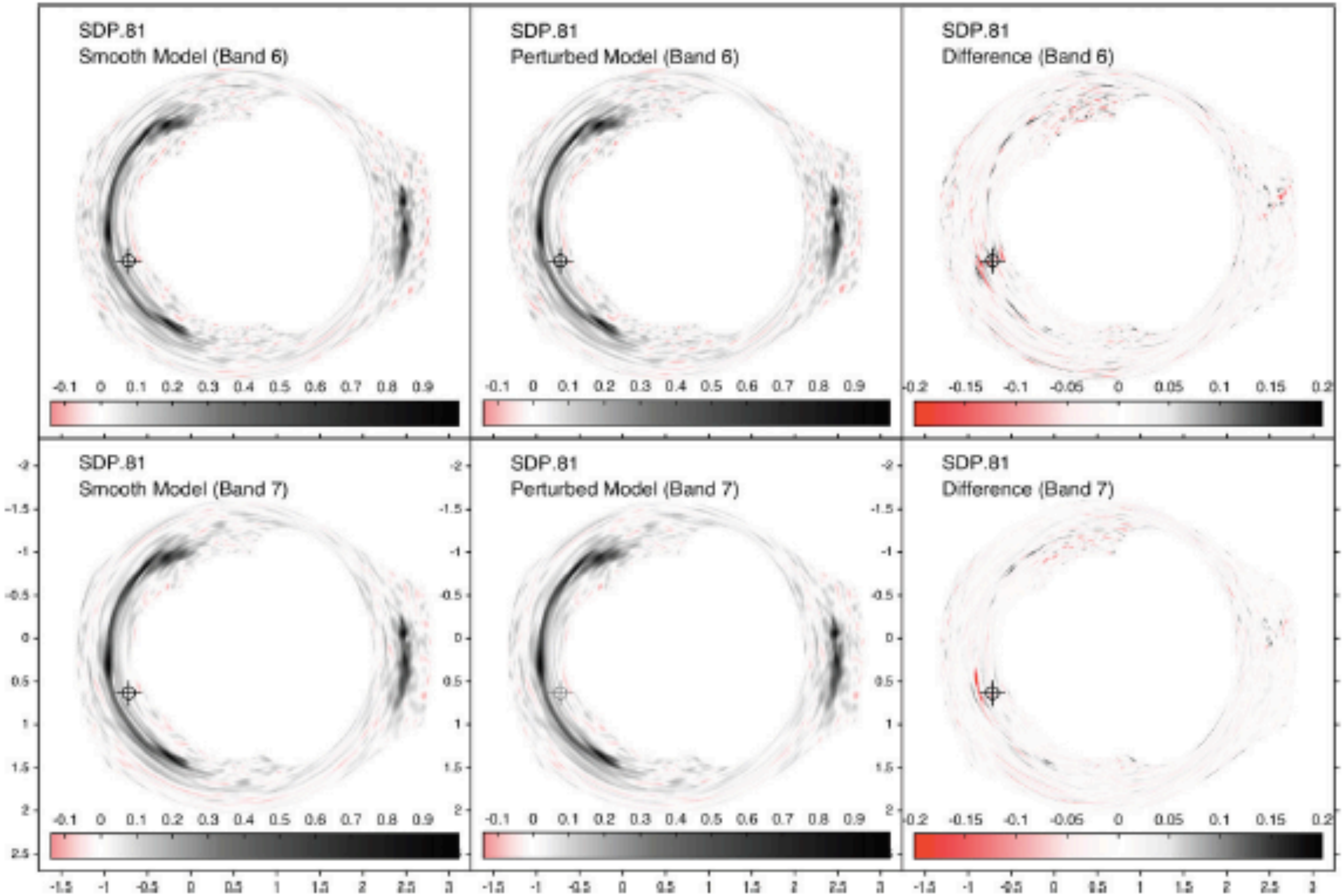


Figure 6. Top left: the sky emission model in band 6 for the best-fit smooth lens parameters for the SDP.81 data. Top middle: the same for the perturbed model. Top right: the difference between the two models. The bottom panels show the same for band 7. The bright feature in the difference plots is mainly caused by the astrometric anomaly of the arc. In each row, the images have been scaled to the peak flux of the smooth model.

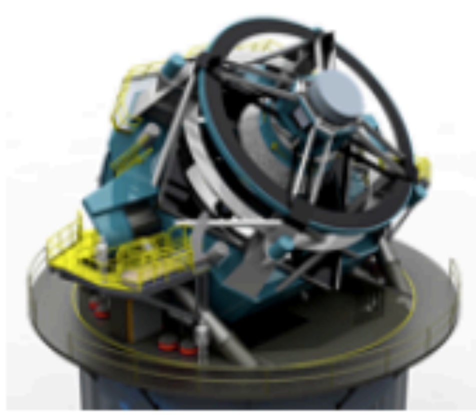
Hezaveh et al., (2016)

LOOKING INTO THE FUTURE:

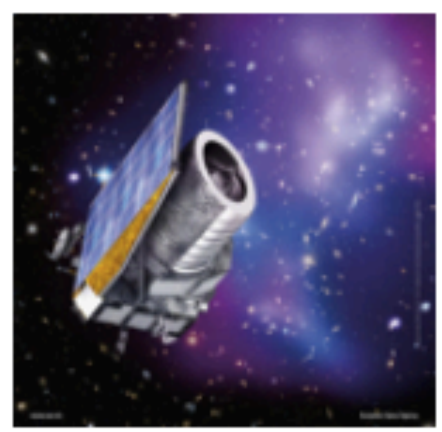
New **Lenses**

For future surveys we find that, assuming Poisson limited lens galaxy subtraction, searches of the DES, LSST, and Euclid data sets should discover **2400**, **120000**, and **170000** galaxy–galaxy strong lenses, respectively

Collett, ApJ. 2015



LSST



euclid consortium

Slides from Laurence Perreault Levasseur

Looking into the future:

Methods?

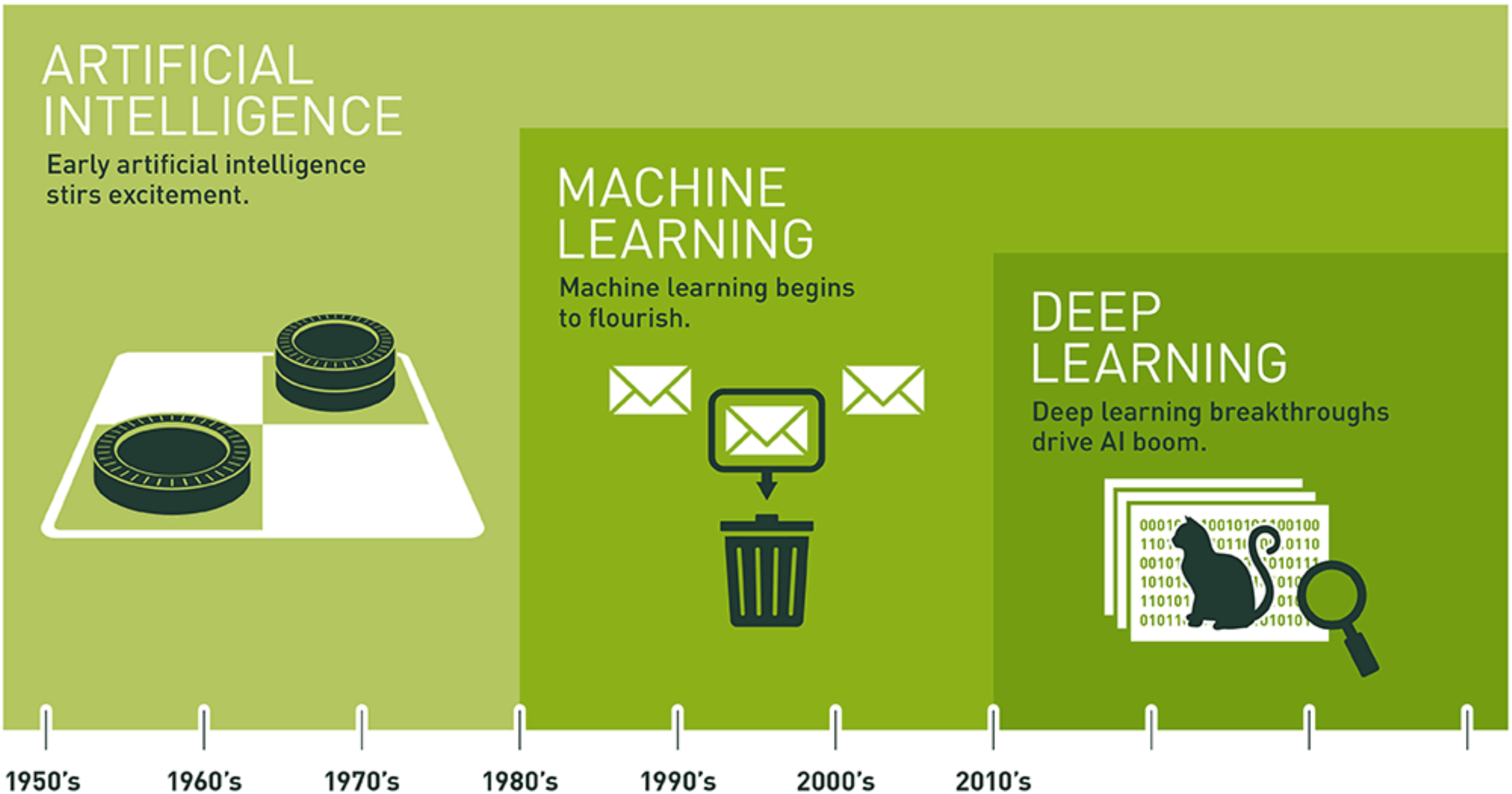
How are we going to analyze 170,000 lenses?

- Lens modeling is **very slow**.
- Even a simple lens model can take 2-3 days of human and CPU time, translating to **1,400 years !!!**
- Even if we pay **100 people** to work on this, it'll be **14 years!!!** Old method are simply not feasible.

Lens modeling sweatshop of 2022

Slides from Laurence Perreault Levasseur

Can AI (deep learning) helps?

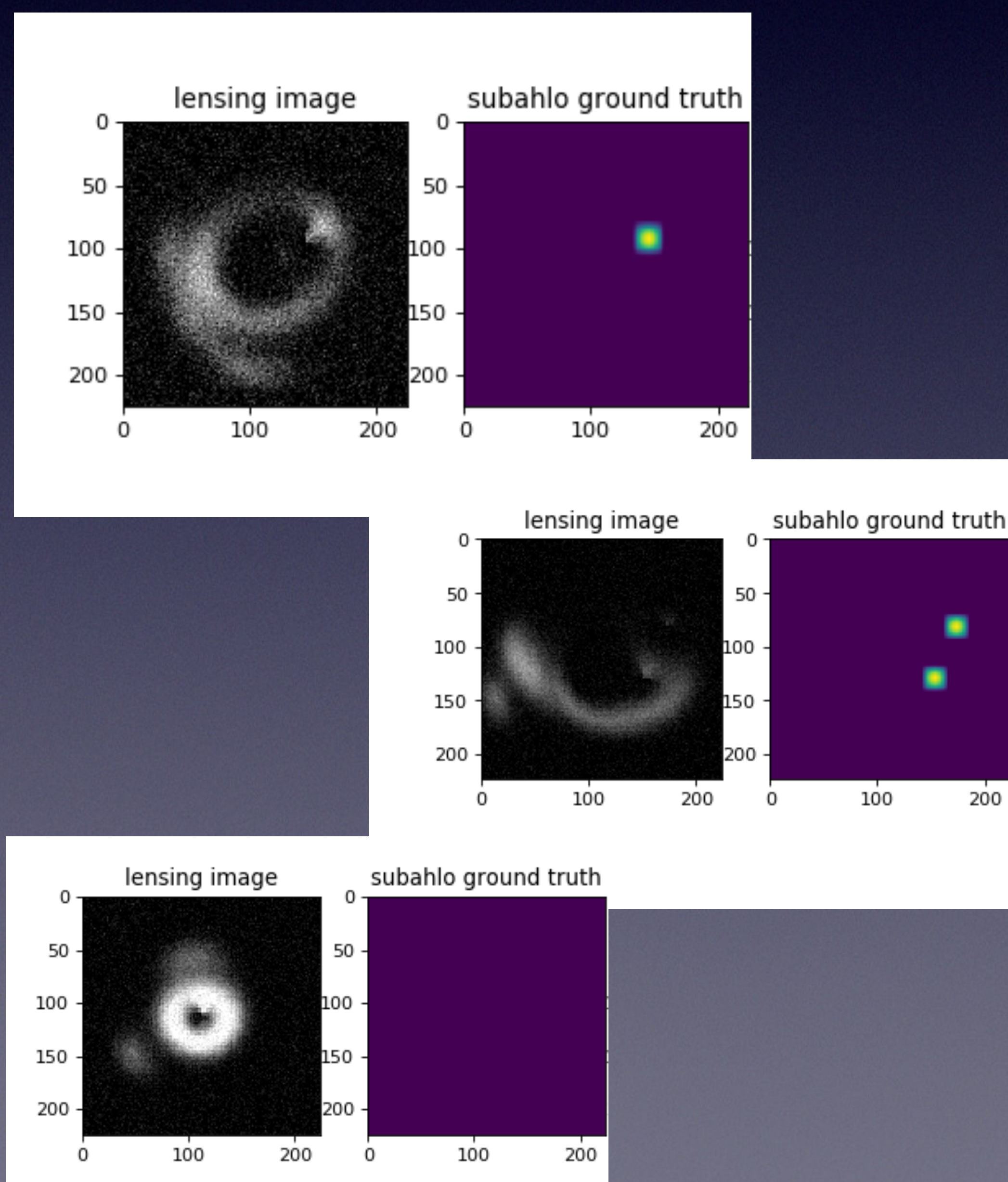


Since an early flush of optimism in the 1950s, smaller subsets of artificial intelligence – first machine learning, then deep learning, a subset of machine learning – have created ever larger disruptions.

Image credit: Nvidia

Deep learning setup

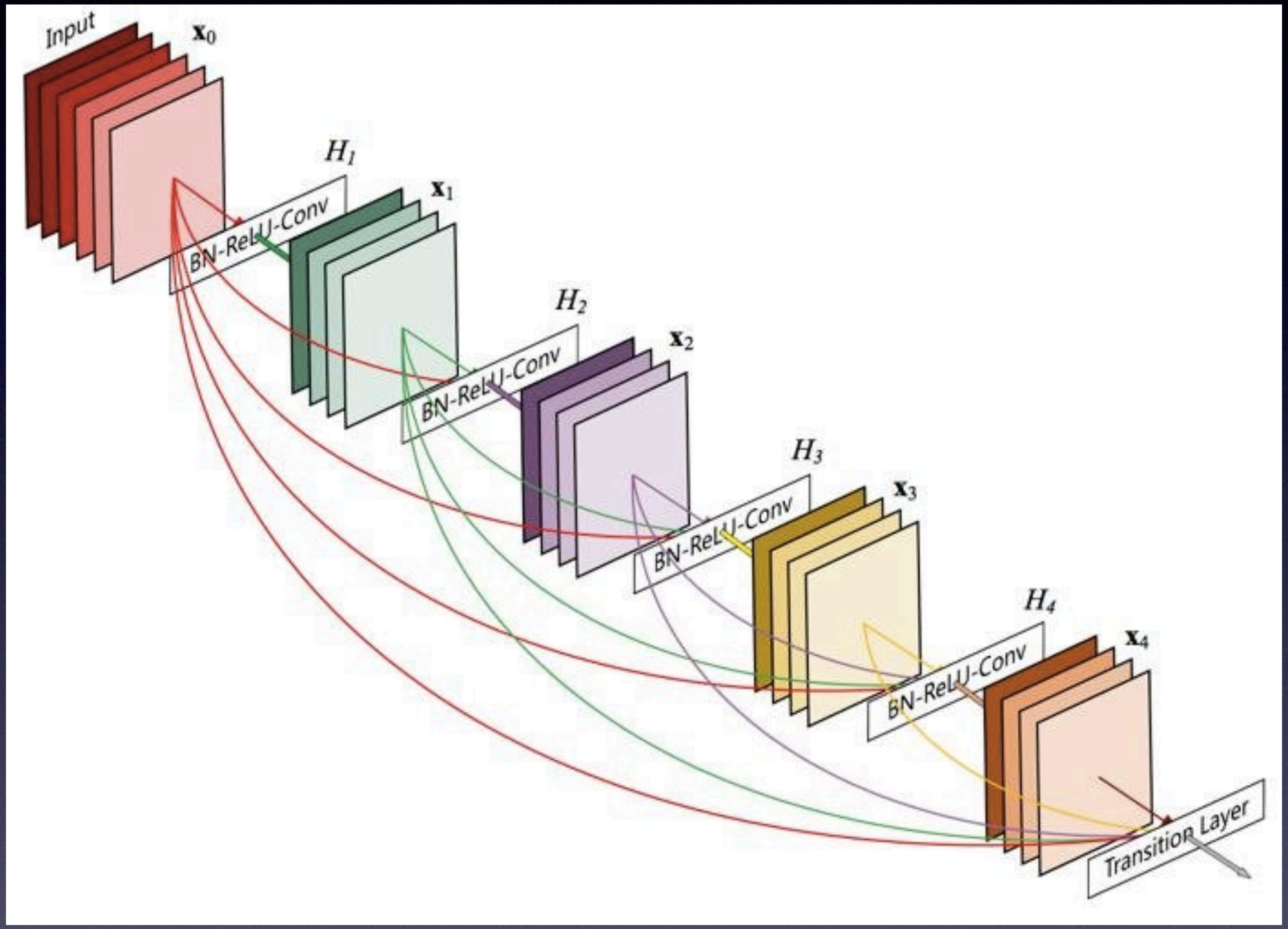
20000 simulated data as training set



- 20000 simulated data [images and subhalo ground truth]as training set
- 2000 “DIFFERENT” data [images] as test set
- Simulation with SIE (marco lens) contains 0-5 subhalos(perturbers)
- Loss function: Binary Cross Entropy with Logits Loss (of subhalo probability map)
- Adam Optimizer, learning rate = 1e-4
- NN model: DenseNet 121
- Nvidia GPU: 1080Ti

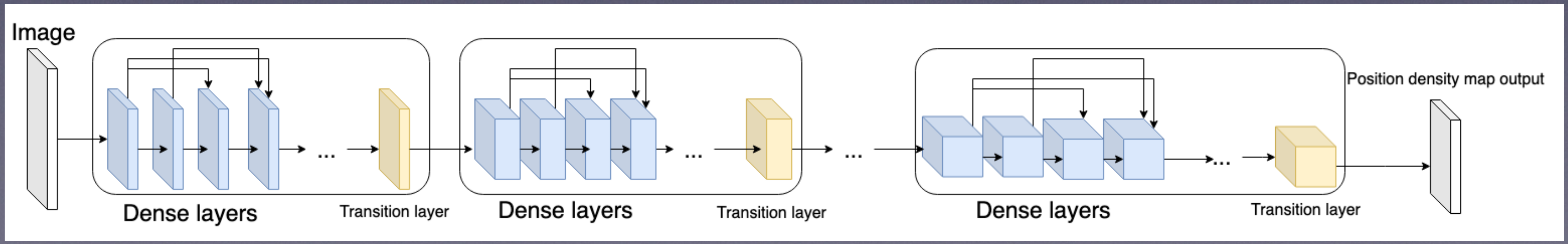
PYTORCH

DenseNet



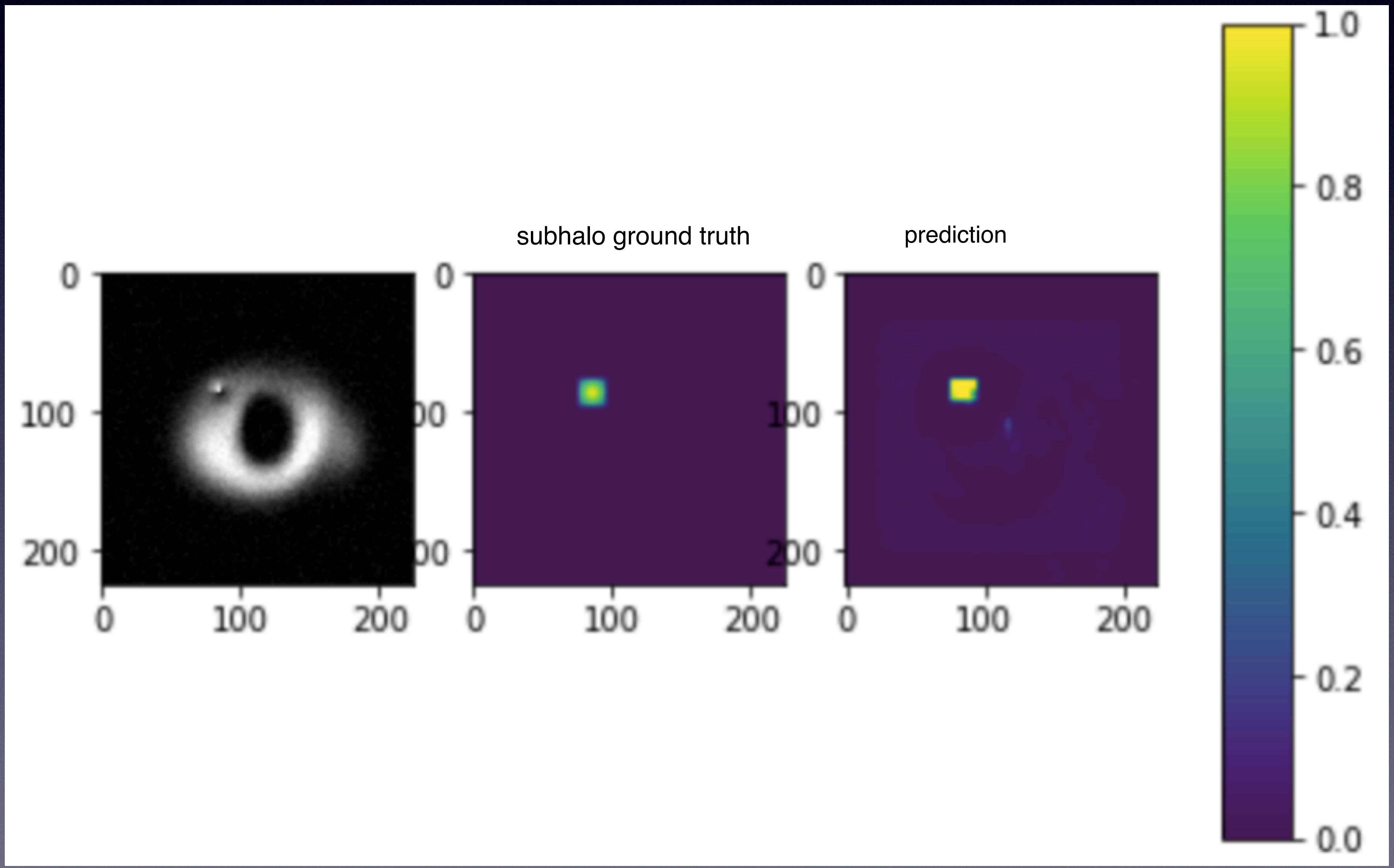
DenseNet architecture (121 layers)

Gao Huang et al., ArXiv:1608.06993

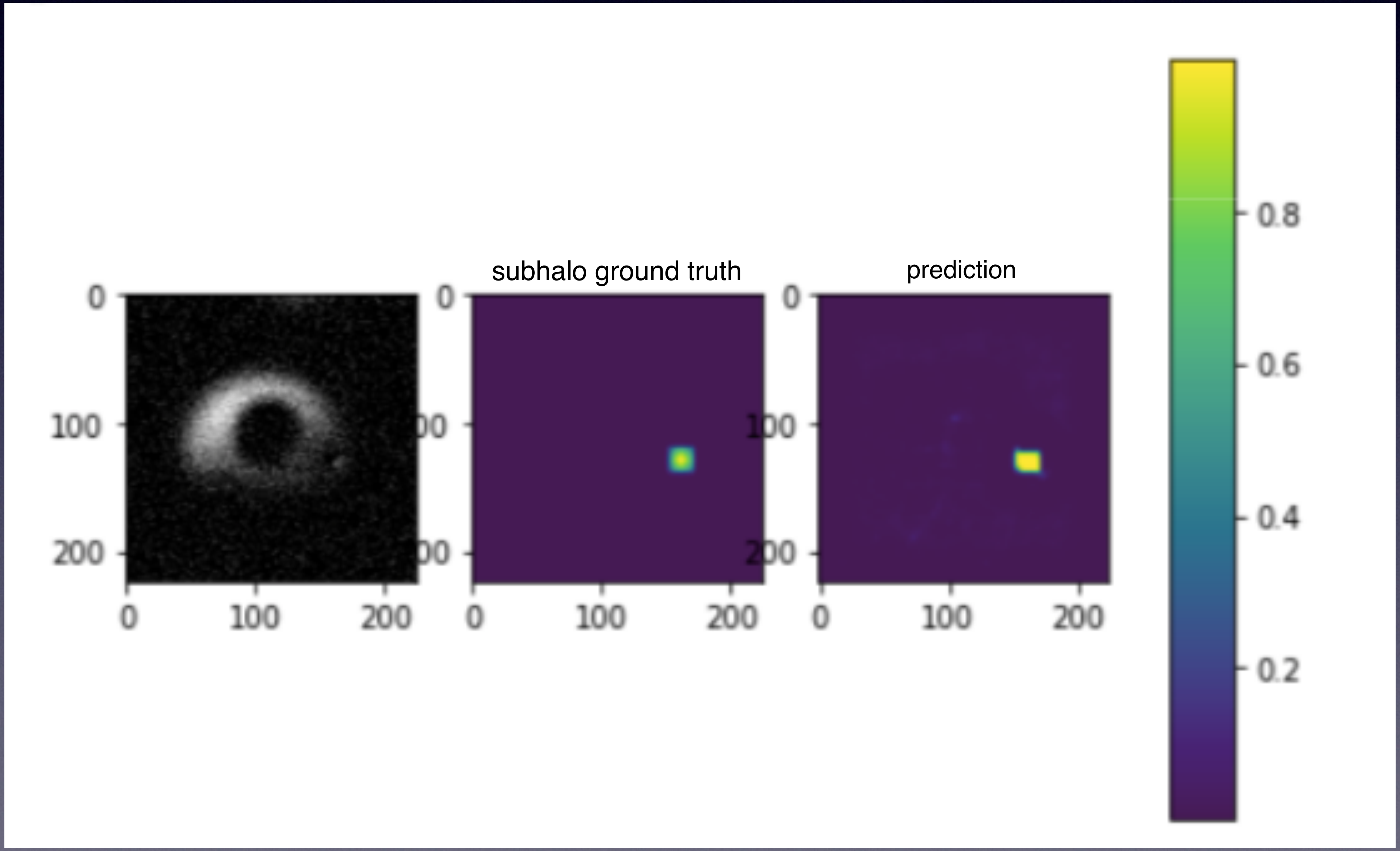


Let’s check how NN is doing

Prediction: subhalo detected!



Prediction: subhalo detected!



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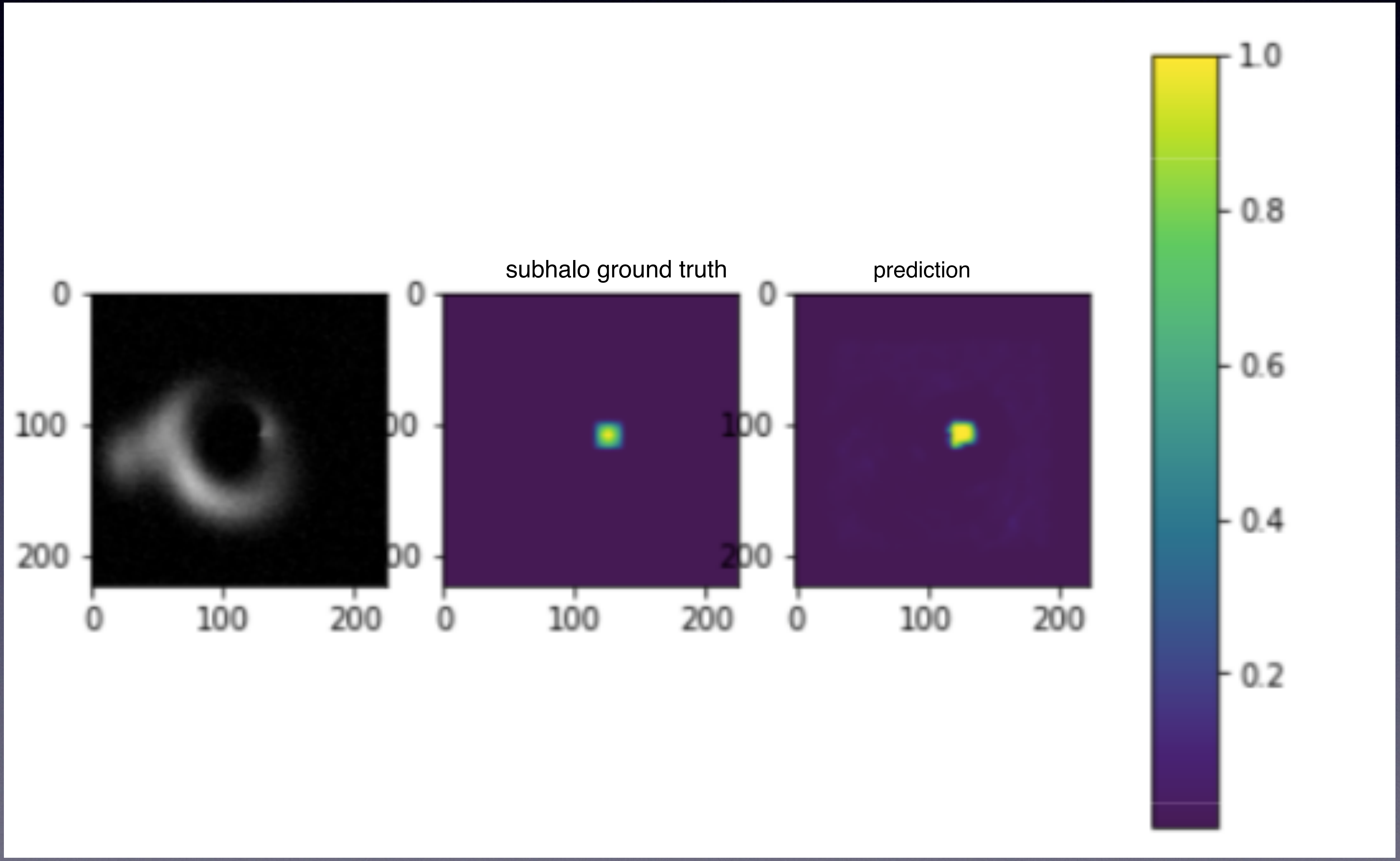
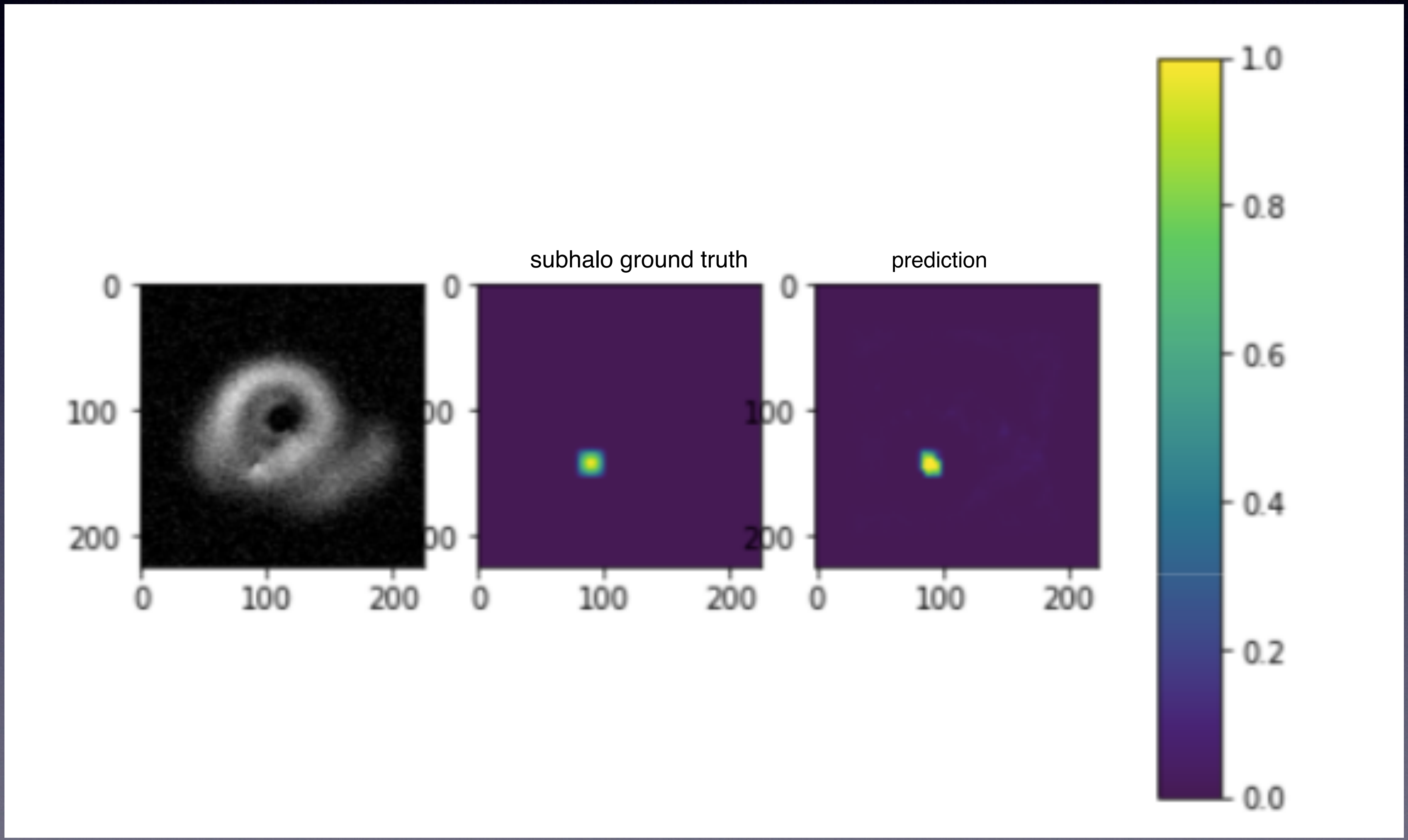
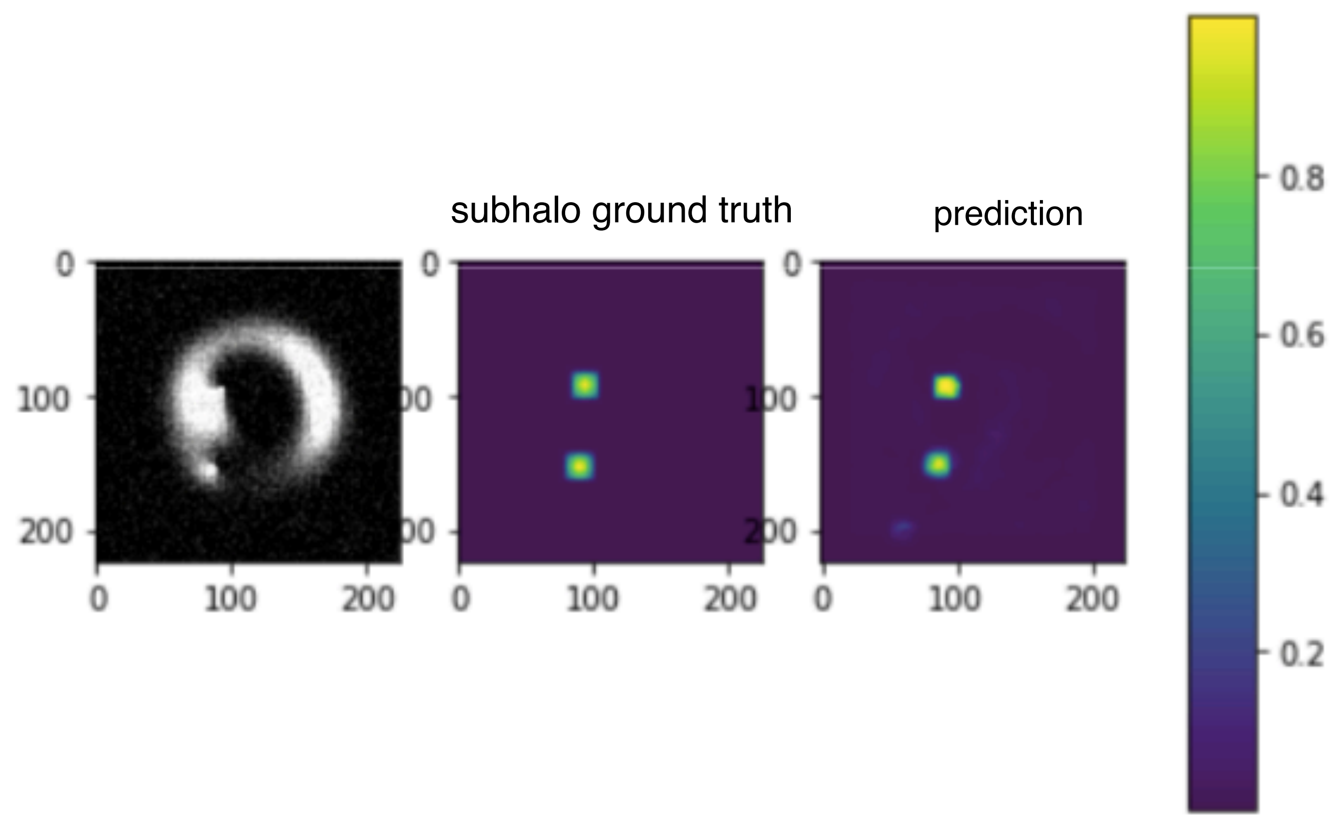


Prediction: subhalo detected!

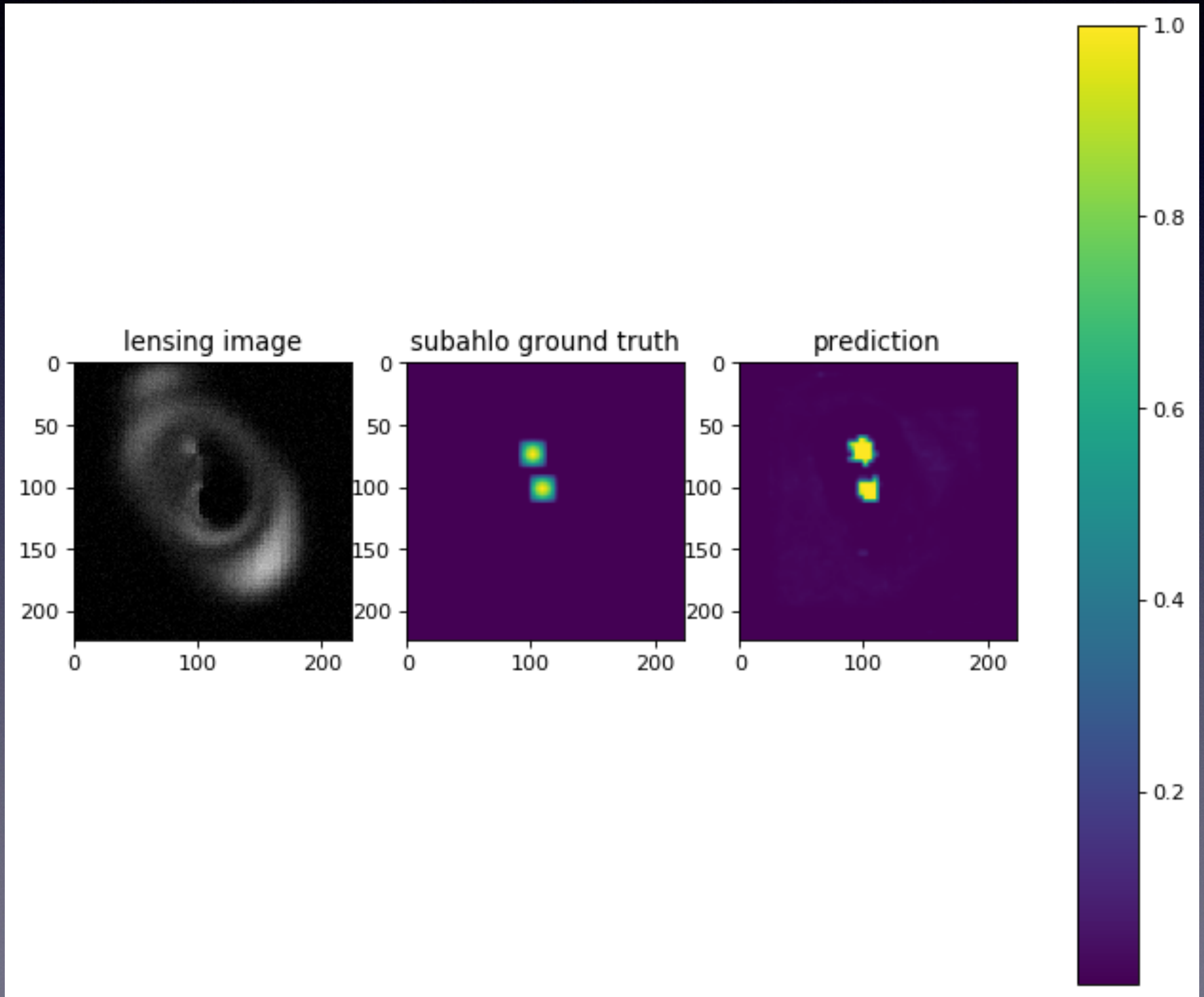


Prediction: multiple subhalos!

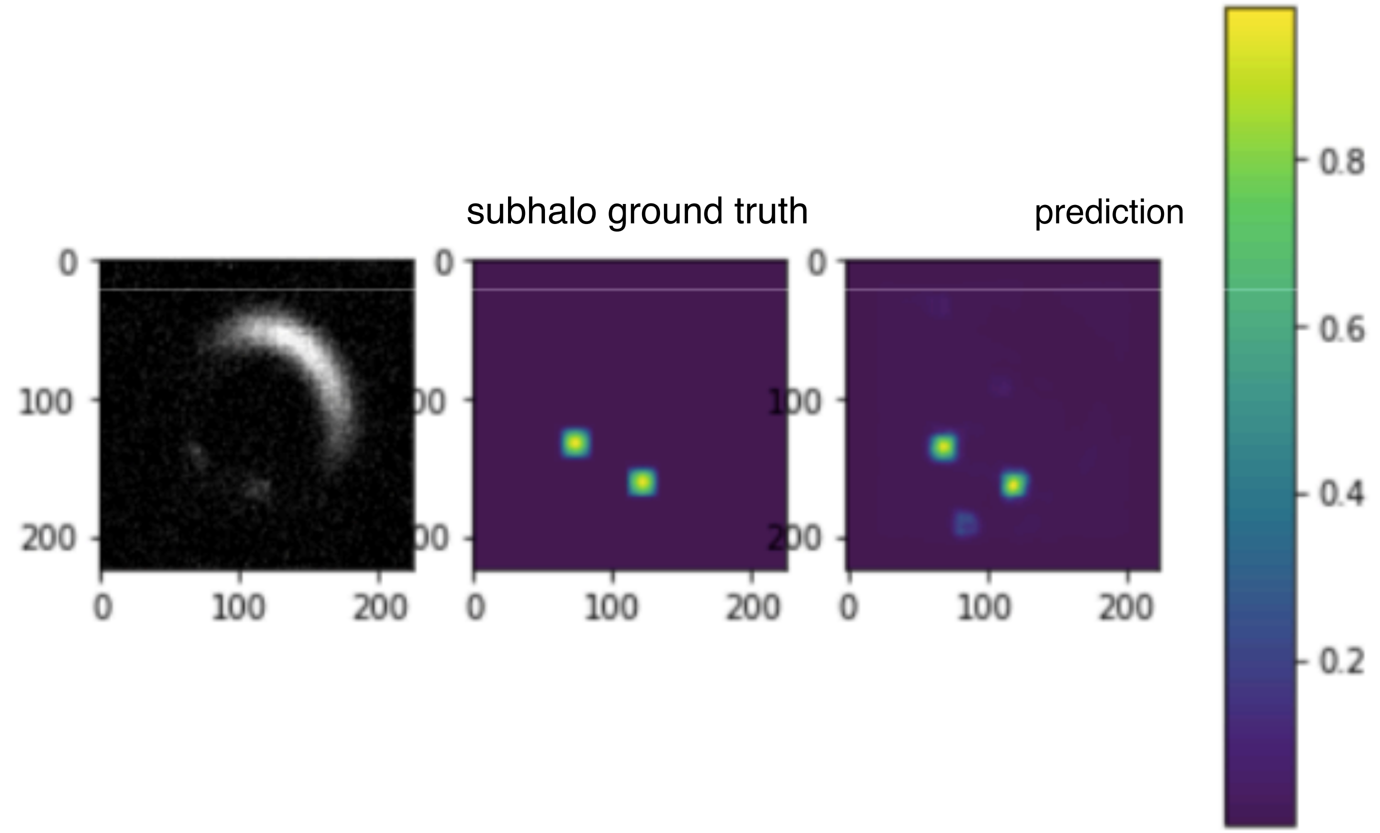



```
Macro:
pred [0.2658, 0.0345, 0.0166, 0.1423, 0.9035, 0.0023, -0.0046, 1.0]
target [ 0.2831 -0.0776  0.1189  0.0781  0.7854  0.        0.        1.     ]
#-----------------------------------------------------------------------
```

Prediction: multiple subhalos!

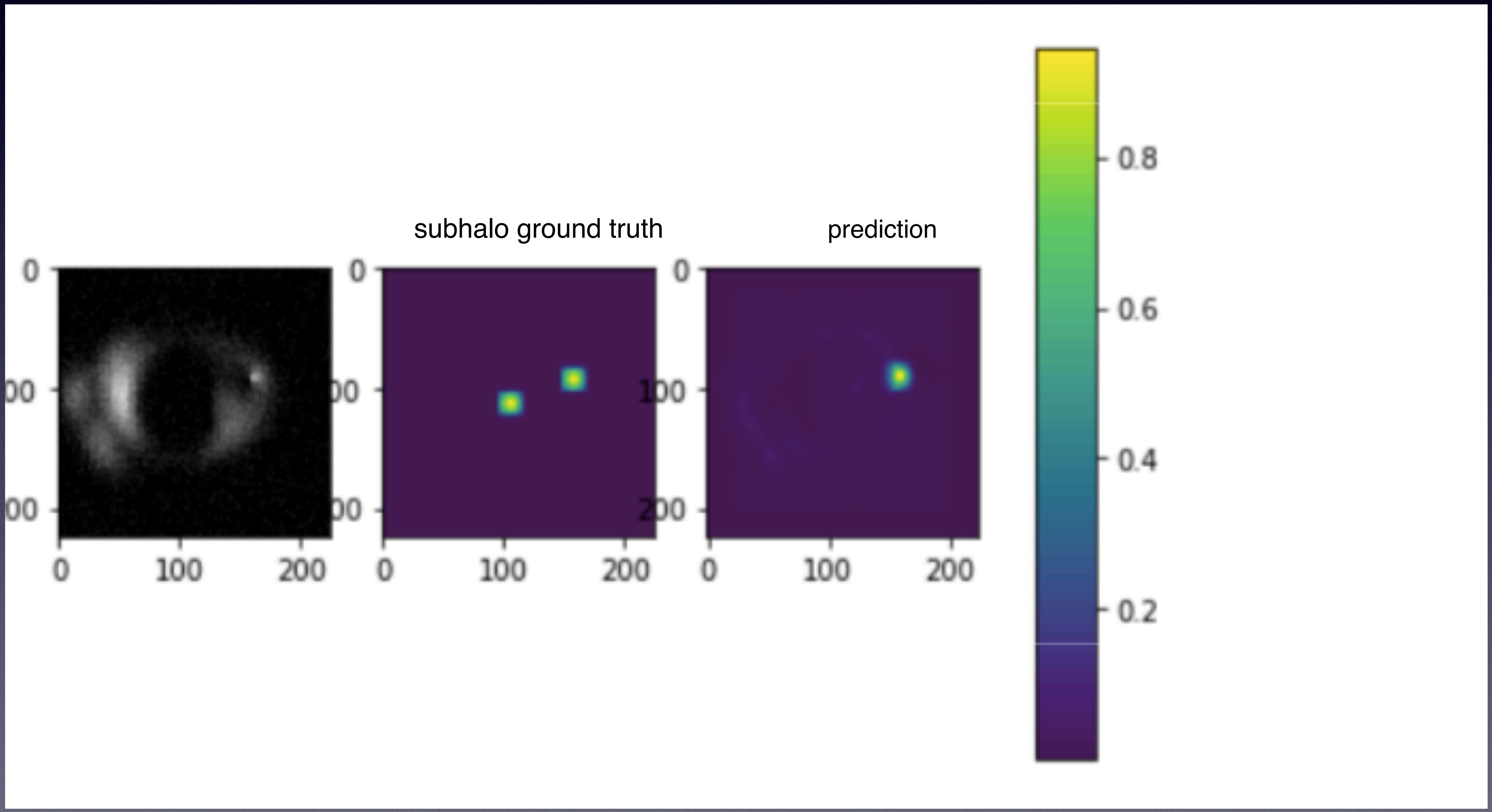


Prediction: multiple subhalos!

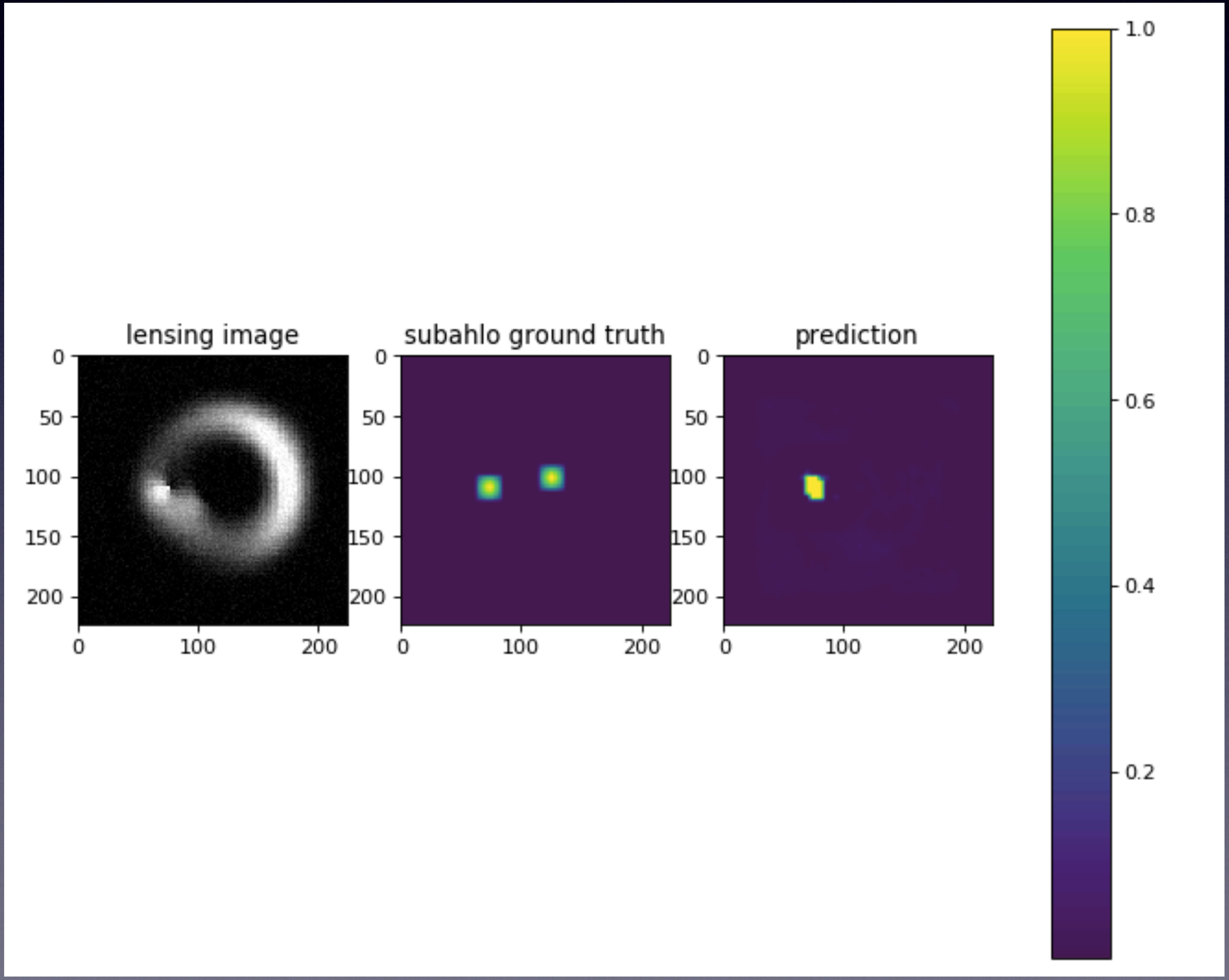



```
Macro:
pred [0.213, 0.064, -0.0276, 0.1478, 0.8645, 0.0065, -0.0043, 1.0]
target [ 0.2699 -0.0707  0.2289  0.0256  0.7854  0.       0.       1.     ]
#---------------------------------------------------------------------
```

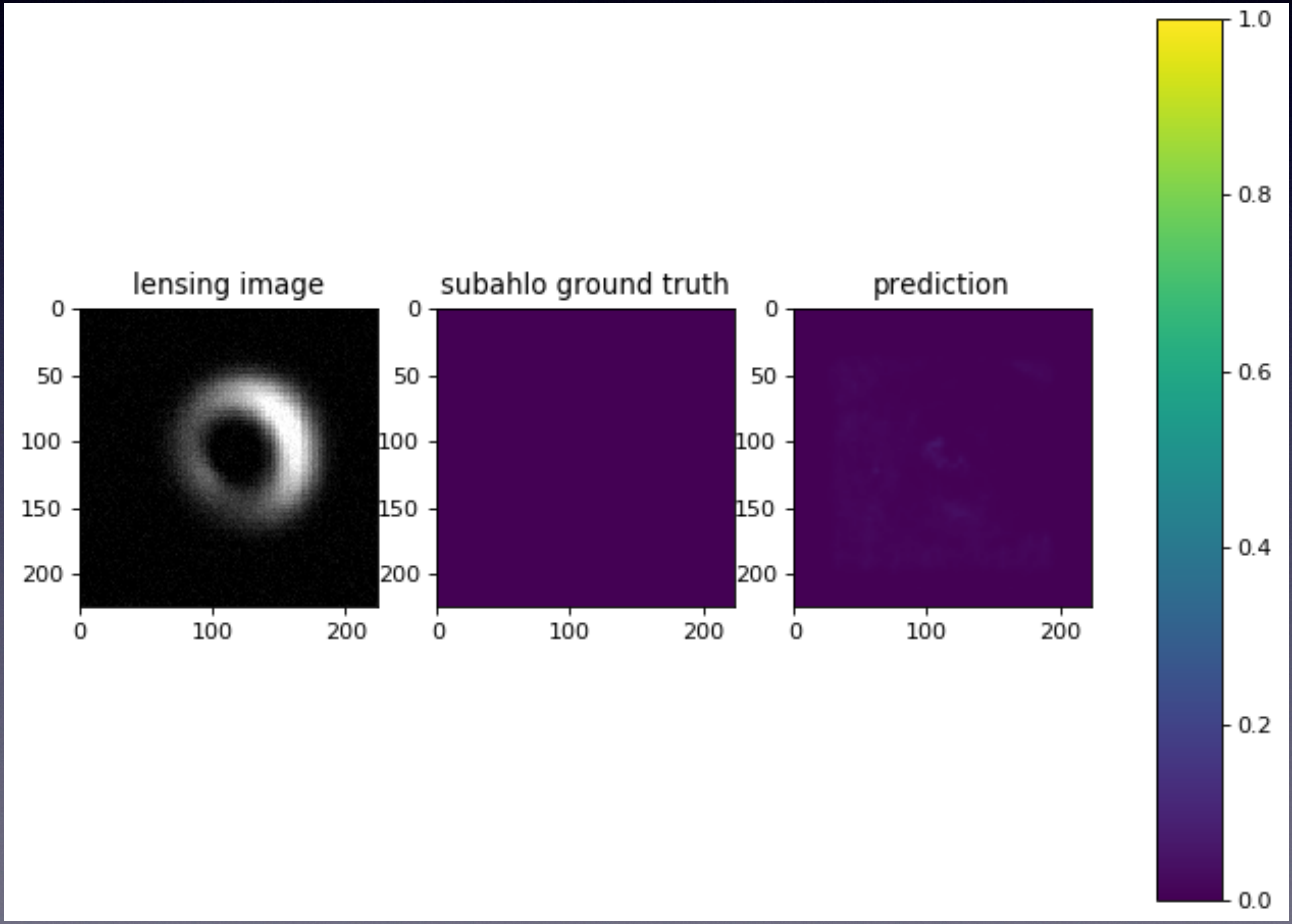
“Failed” good examples: Can’t see in the dark



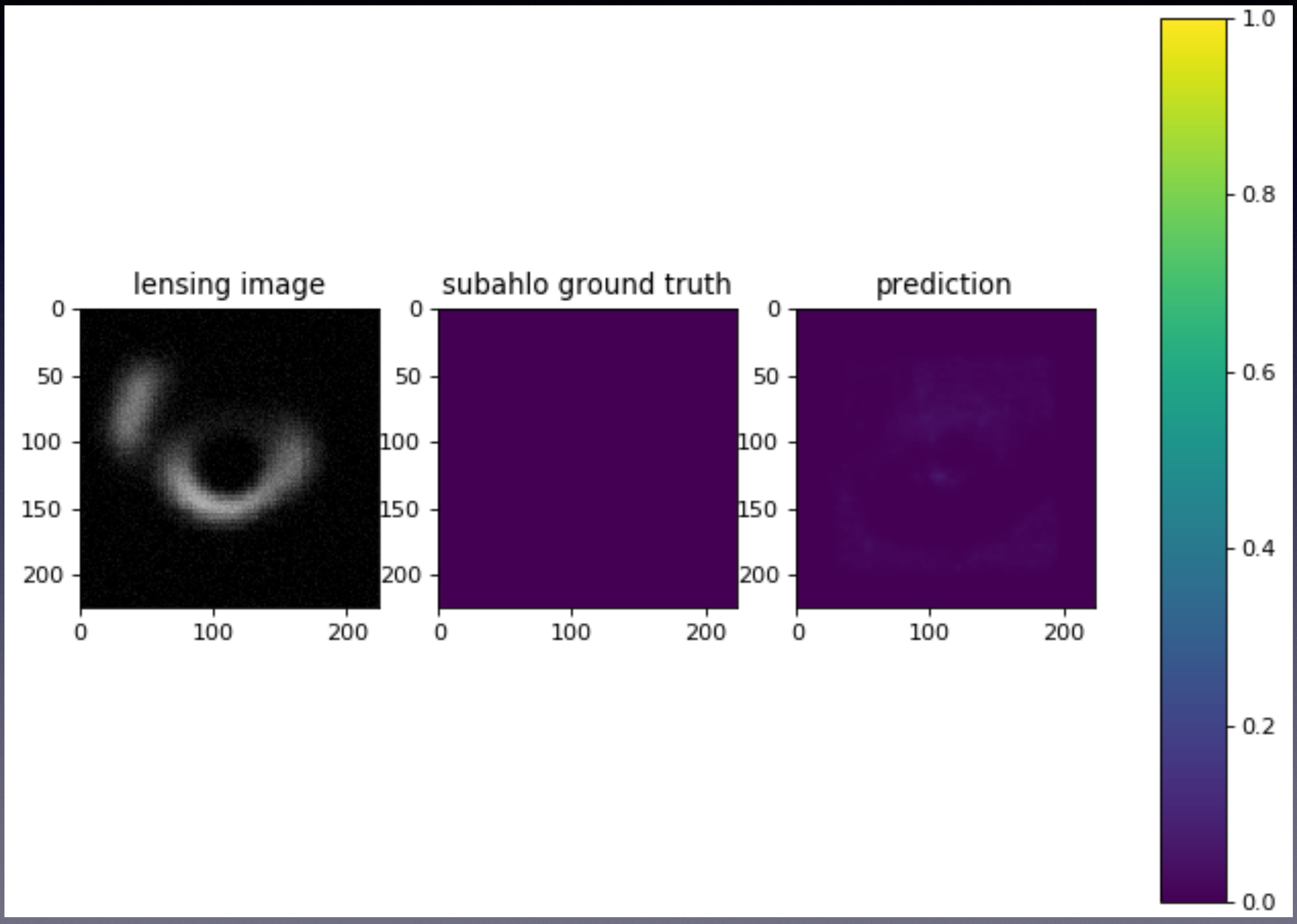
“Failed” good examples: Can’t see in the dark



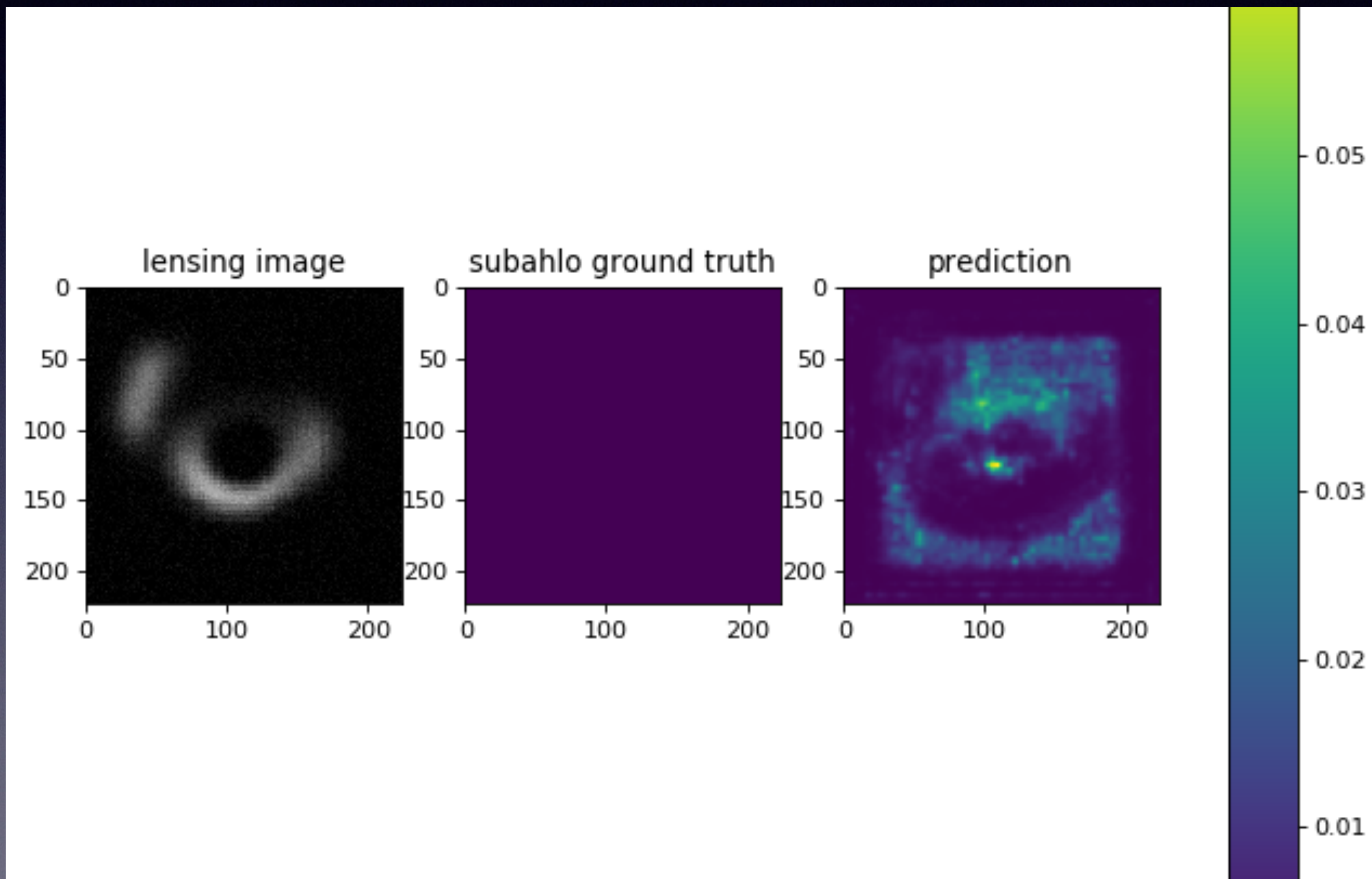
Prediction: No subhalo



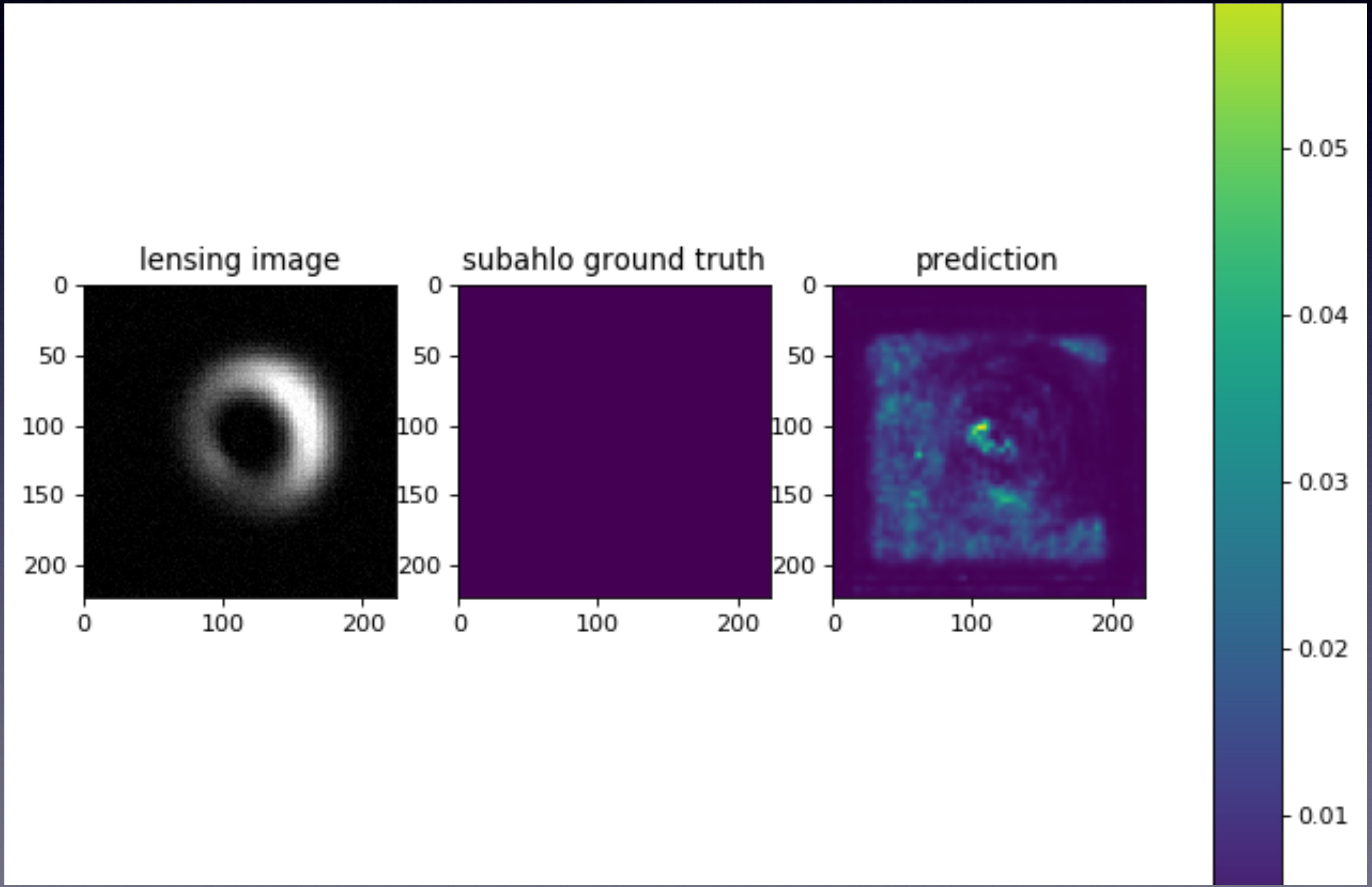
Prediction: No subhalo



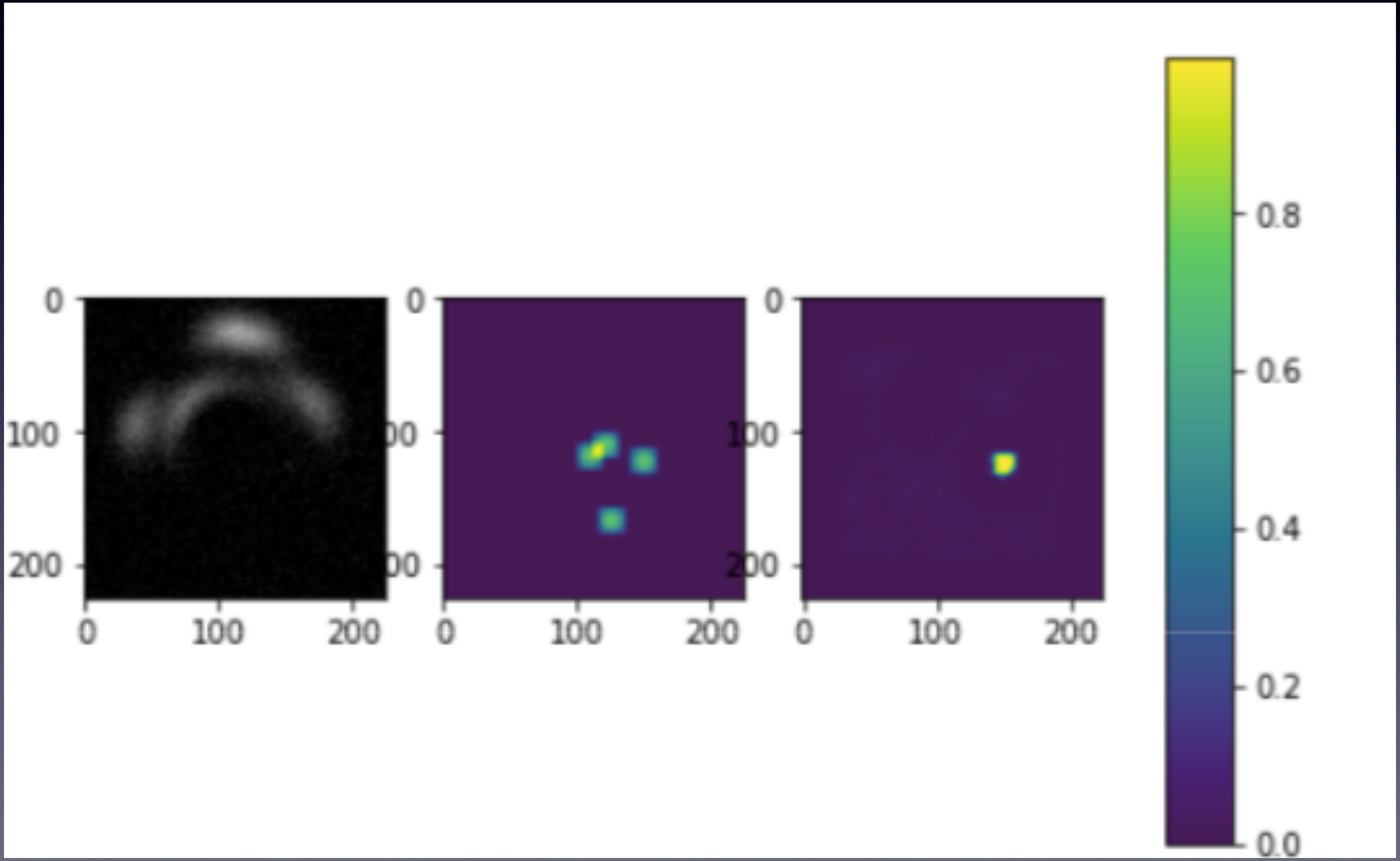
“Rejection” of subhalo(s) around the arc



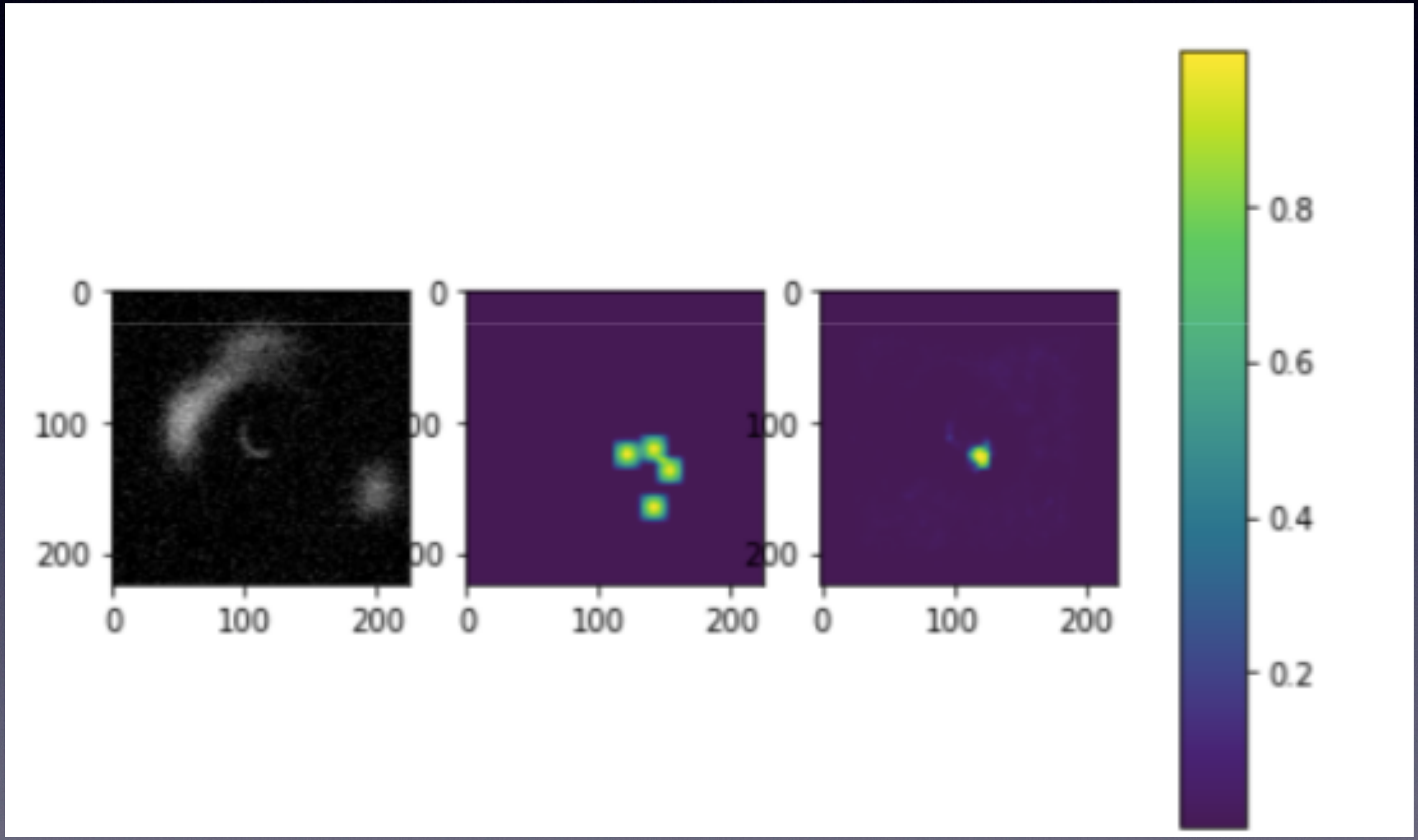
“Rejection” of subhalo(s) around the arc



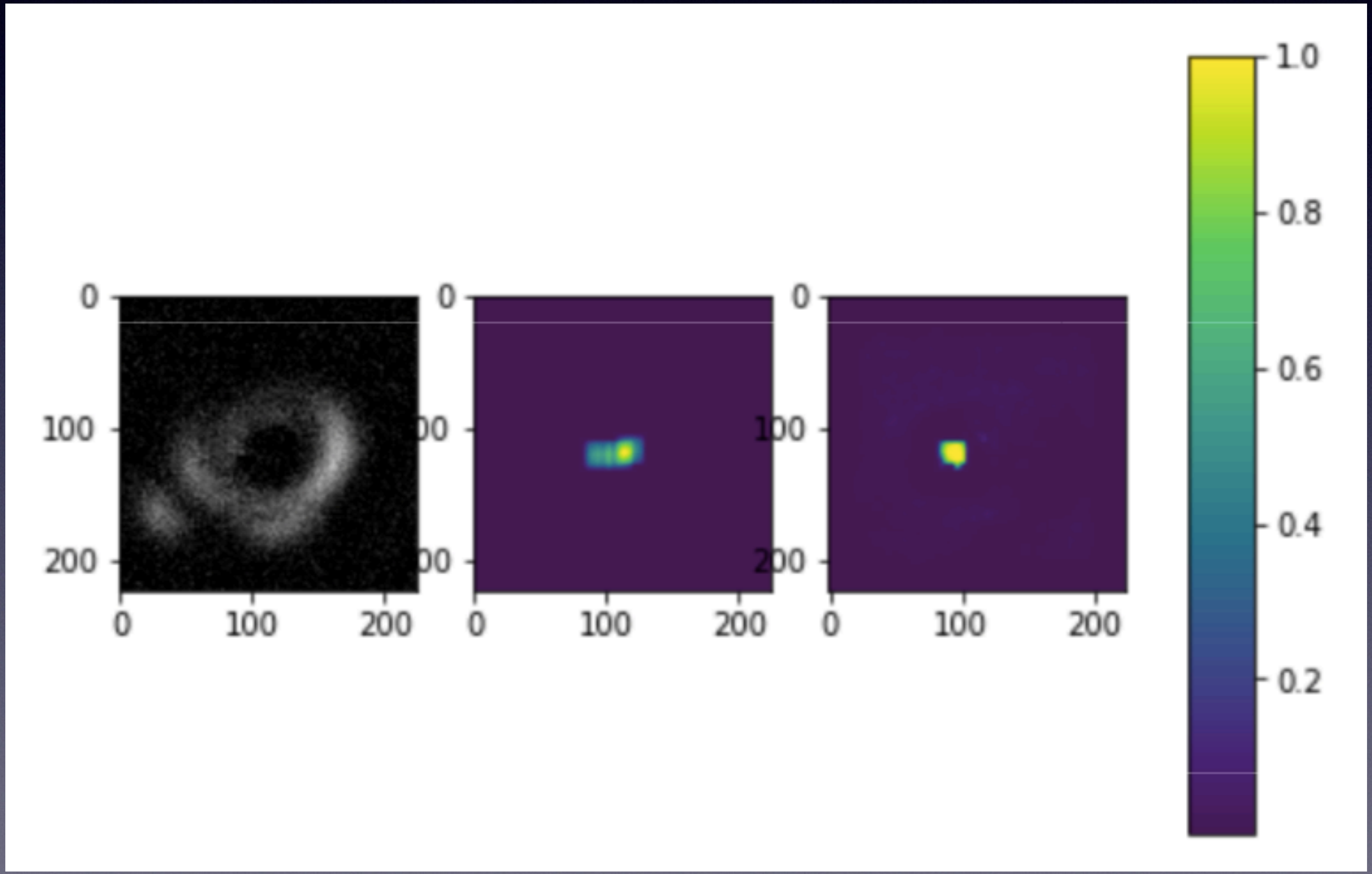
"Failed" prediction: Are they learning center of the mass?



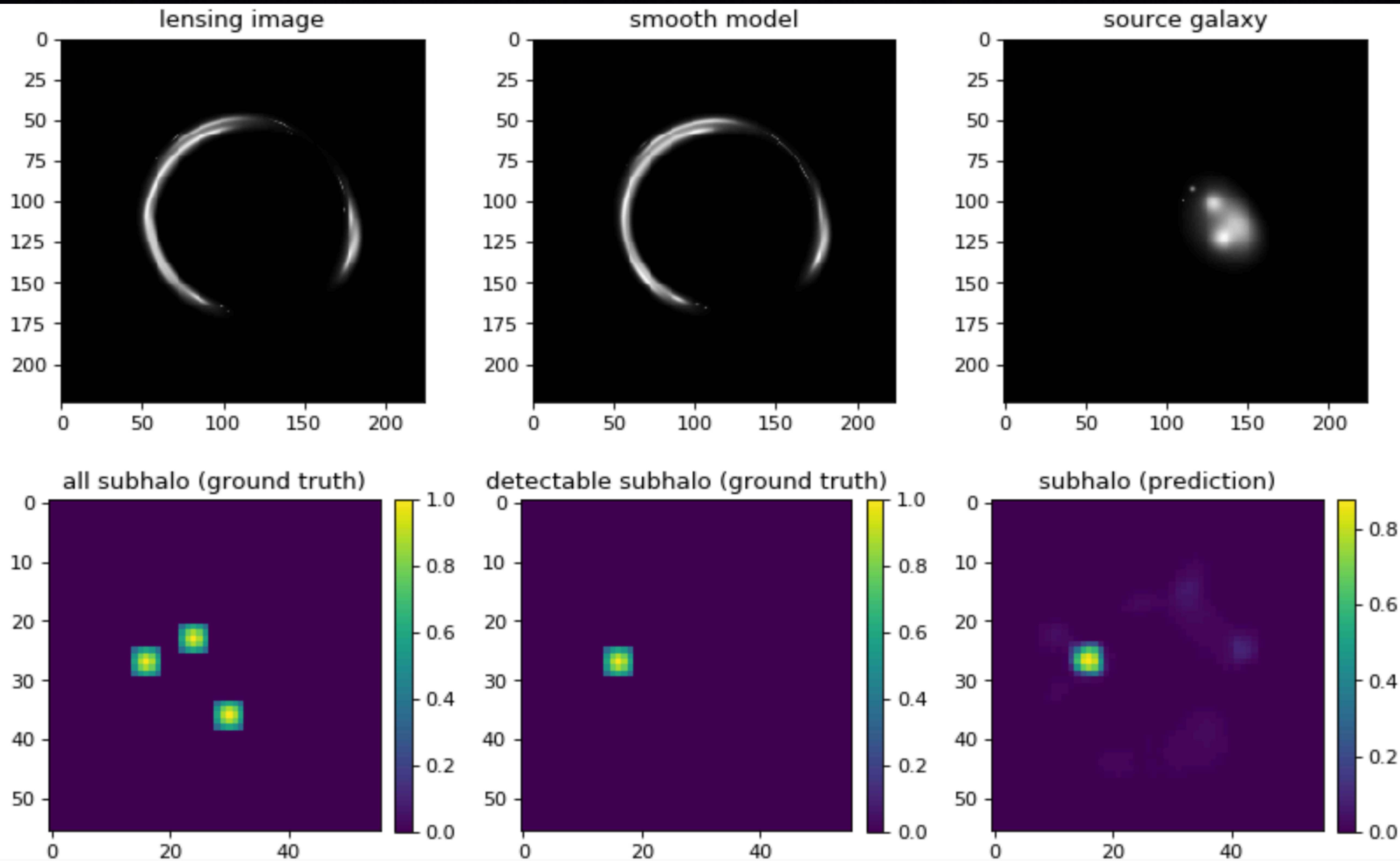
"Failed" prediction:
Are they learning center of the mass?

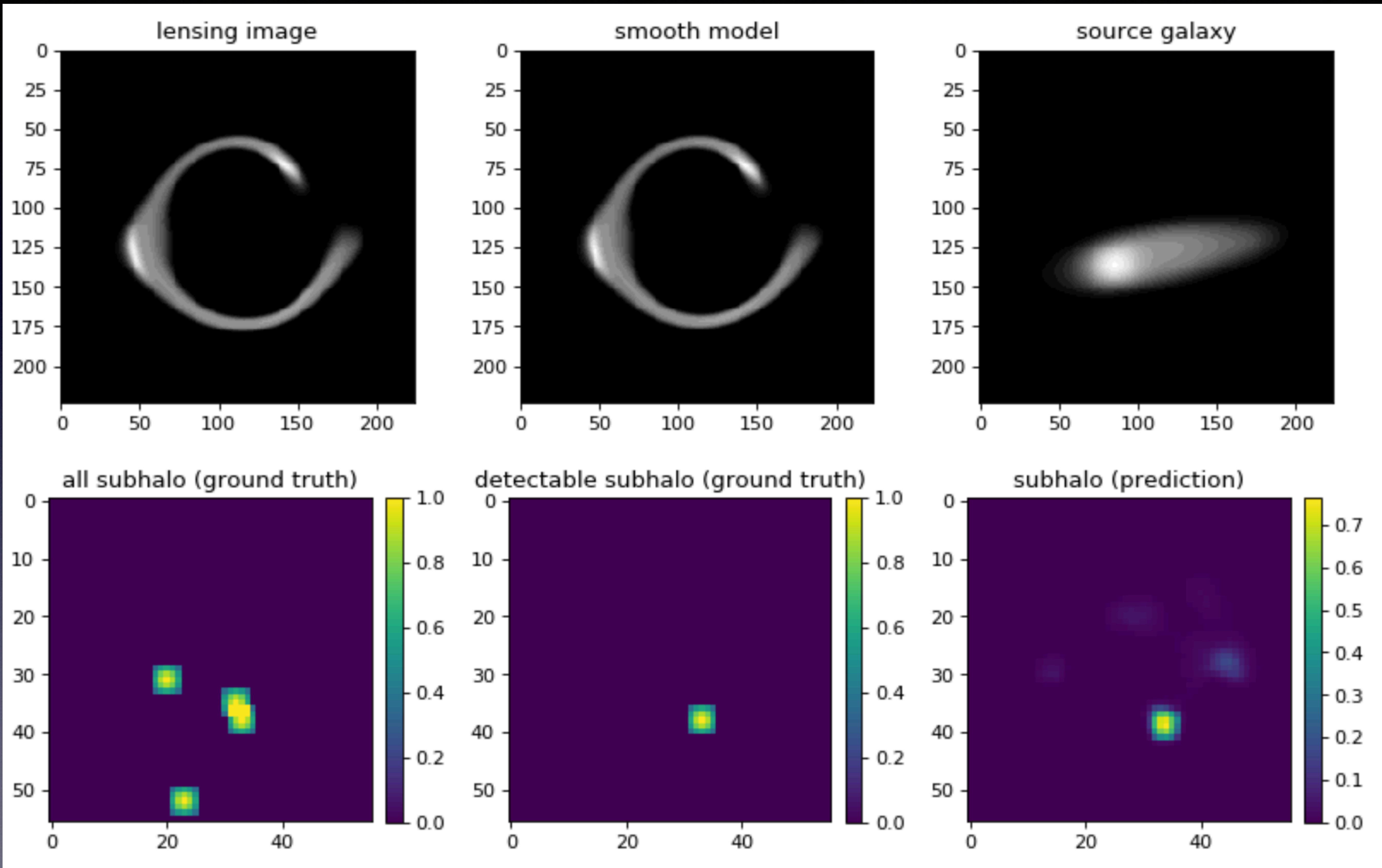


“Failed” prediction:
Are they learning center of the mass?

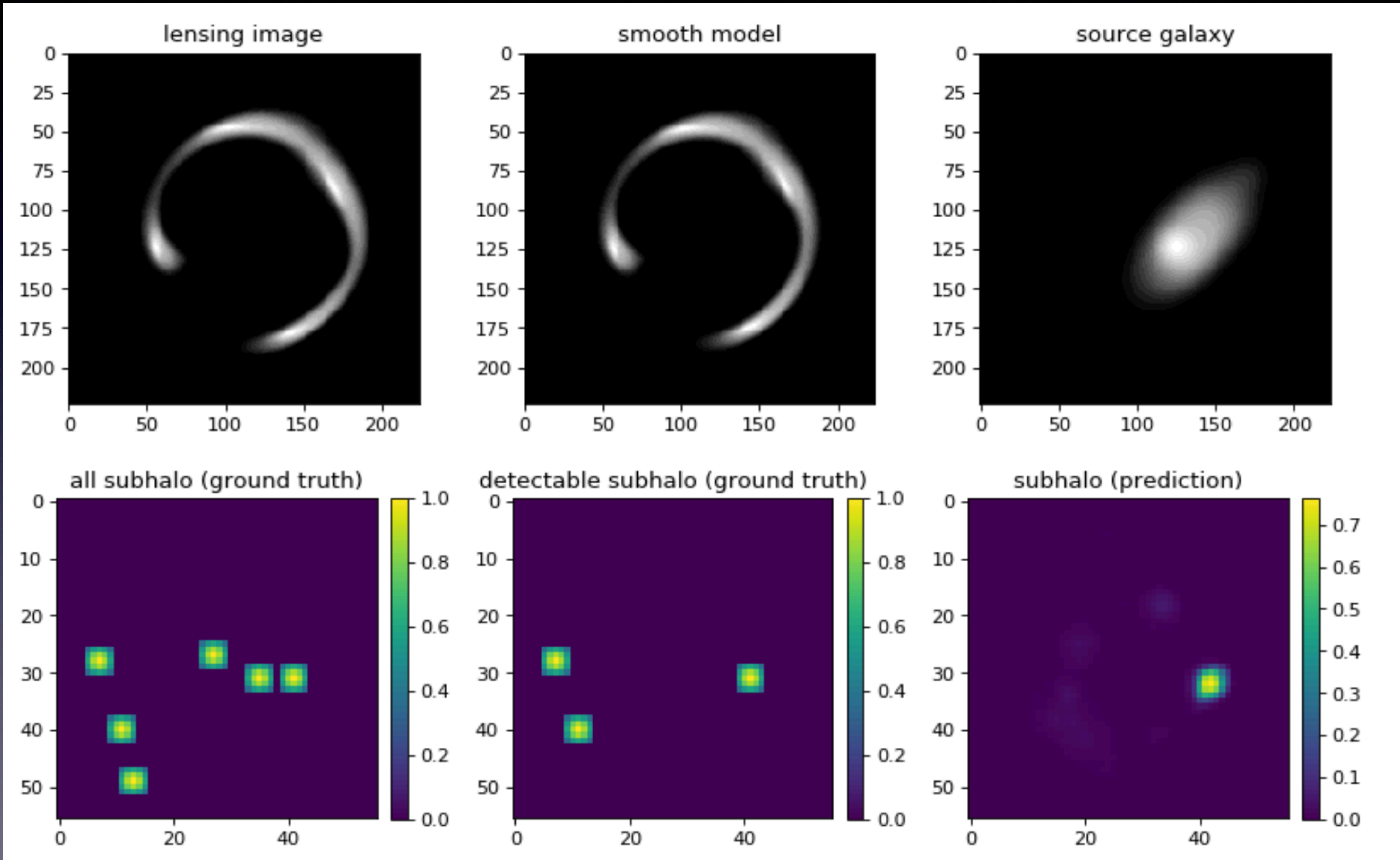


Realistic simulation





lensing image
smooth model
source galaxy
all subhalo (ground truth)
detectable subhalo (ground truth)
subhalo (prediction)



lensing image
smooth model
source galaxy
all subhalo (ground truth)
detectable subhalo (ground truth)
subhalo (prediction)

Summary for this project

- Deep learning shows some promising result in dark matter substructures detection in lensing.
- “rejections” for no subhalos around the strong lensing arc.
- “detections” and “regression” for subhalos around the strong lensing arc.
- Learning from the NN output might also be interesting (intuitive physics), should be investigate more.
- Generating more realistic simulated data and analyzing real data would be coming soon!

Thank you!

Image Credit: Hubble/STScI & NASA